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Research article

Time-resolved quantitative evaluation of diaphragmatic motion during forced breathing in a health screening cohort in a standing position: Dynamic chest phrenicography

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ABSTRACT

Objective: To assess diaphragmatic motion during forced breathing in a health screening center cohort by time-resolved quantitative analysis using dynamic chest radiography and demonstrate the characteristics and associations with demographics and pulmonary function of participants.

Materials and methods: This prospective study includes 174 volunteers (99 males; median 57, range 36–93 years old) that underwent dynamic chest radiography with a flat panel detector system during forced breathing in a standing position. We automatically tracked and recorded the positions of the top of the diaphragms and the excursions on images of each participant and calculated peak motion speeds based on the data. We investigated the associations with demographics and pulmonary function statistically.

Results: The average excursions of the diaphragms during forced breathing were 49.1 ± 17.0 mm (right; mean ± standard deviation) and 52.1 ± 15.9 mm (left). The peak motion speeds were 26.7 ± 10.0 mm/s (right) and 32.2 ± 12.4 mm/s (left) in the inspiratory phase and 22.1 ± 12.7 mm/s (right) and 24.3 ± 10.3 mm/s (left) in the expiratory phase. Excursions and peak motion speeds of the left diaphragm were significantly greater than the right. Higher body mass index (BMI) and vital capacity (VC) were associated with greater excursions and faster peak motion speeds of the diaphragms.

Conclusions: Time-resolved quantitative analysis of the diaphragms with dynamic chest radiography demonstrated the characteristics of diaphragmatic motion during forced breathing in a health screening cohort. Higher BMI and VC were associated with excursions and peak motion speeds of the diaphragms.

1. Introduction

One of the essential organs for respiration, the diaphragm is a dome-shaped structure of muscular and fibrous septum separating the thoracic and abdominal cavities. Dysfunction of the diaphragm is common and can be caused by trauma, surgery, cervical cord or phrenic nerve damage, inflammation and mediastinal mass, and various other reasons [1]. Functional analysis and quantification of motion for diaphragms have been performed using many imaging modalities, including conventional chest radiography [2–4], fluoroscopy [5–7], ultrasonography (US) [8–12], computed tomography (CT) [13], and magnetic resonance imaging (MRI) [14–16]. However, while understanding diaphragm kinetics is useful for monitoring, treatment, and management of respiratory diseases with diaphragm dysfunction the diaphragm's function and contribution to respiratory difficulties have not been fully investigated.

Abbreviations: BMI, body mass index; COPD, chronic obstructive pulmonary disease; CT, computed tomography; FEV_1, forced expiratory volume in one second; GOLD, global initiative for chronic obstructive pulmonary disease; MR, magnetic resonance; SD, standard deviation; US, ultrasonography; VC, vital capacity

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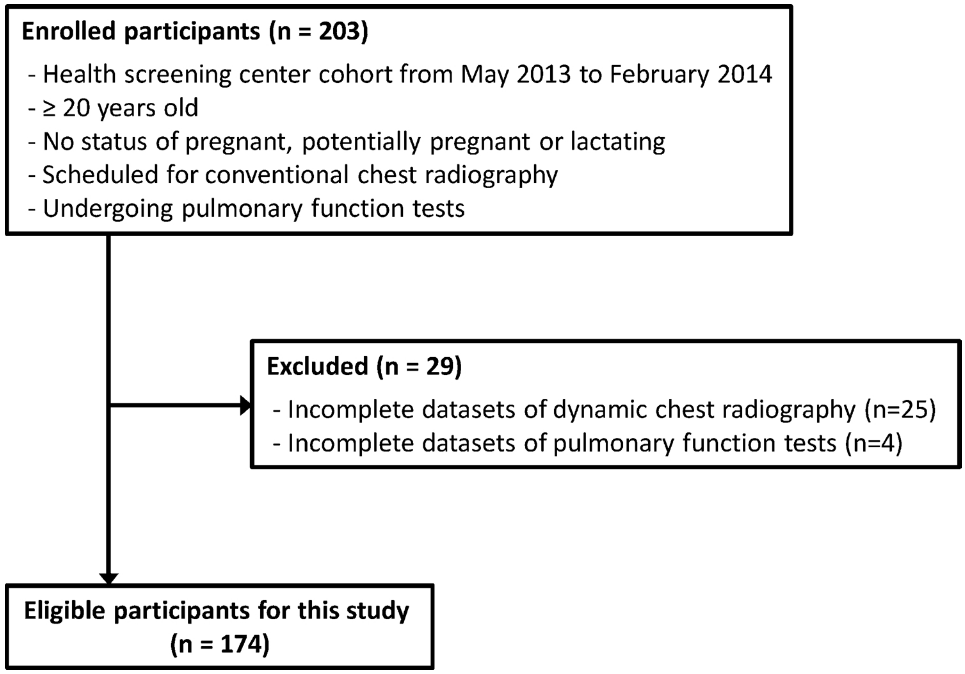

Fig. 1. Flow diagram of the study population.

Dynamic chest radiography using a flat panel detector (FPD) with a large field of view was introduced for clinical use recently [17]. This technique obtains high temporal resolution sequential chest radiographs during respiration with a low radiation dose by a simple procedure comparable to conventional chest radiography [18] and provides objective and quantifiable information, including pulmonary ventilation and circulation, cardiovascular function, and diaphragm kinetics [17–19]. Dynamic chest radiography, or "dynamic X-ray phrenicography", is expected to provide more information than ever about the kinetics and function of the diaphragm as an essential organ in external respiration. Yamada et al. previously applied this technique for the assessment of diaphragm dynamics in a standing position for tidal breathing in normal subjects and chronic obstructive pulmonary disease (COPD) patients and demonstrated its usefulness [20,21]. Diaphragmatic motion during forced breathing is expected to reflect dynamics of the diaphragm and pulmonary function more than during tidal breathing. To the best of our knowledge, however, no previous study has analyzed diaphragmatic motion during forced breathing using dynamic chest radiography.

The aim of this study is to assess diaphragmatic motion in a standing position during forced breathing by time-resolved quantitative analysis using dynamic chest radiography in a health screening center cohort and evaluate any associations with demographics and pulmonary function of the participants.

2. Materials and methods

2.1. Cohort selection

This prospective study was approved by the institutional review board and all participants provided written informed consent before participation. Two hundred and three individuals who underwent health screening in our institution consecutively from May 2013 to February 2014 and met the following criteria were recruited in this study: (a) ≥20 years old; (b) no status of pregnant, potentially pregnant or lactating; (c) scheduled for conventional chest radiography; (d) undergoing pulmonary function tests. Individuals with incomplete data sets of dynamic chest radiography (n = 25) or incomplete data sets of pulmonary function tests (n = 4) were excluded. A total of 174 individuals were eligible for the analysis (Fig. 1). The data from 172 participants of this cohort has been analyzed in the prior study of dynamic chest radiography that dealt with diaphragmatic motion during tidal breathing [20], whereas we analyzed diaphragmatic motion during forced breathing in this study.

All participants underwent pulmonary function tests on the same day of dynamic chest radiography using a pulmonary function instrument with computer processing (DISCOM-21 FX, Chest MI Co, Tokyo, Japan). Parameters of pulmonary function tests were recorded according to the American Thoracic Society guidelines [22]. The heights and weights of all participants were measured and body mass index (BMI, or weight in kilograms divided by height in meters squared) was calculated.

2.2. Imaging protocol of dynamic chest radiology-radiography

Posteroanterior dynamic chest radiography was performed in the standing position using a prototype X-ray system (Konica Minolta Inc., Tokyo, Japan) composed of an FPD (PaxScan 4030CB, Varian Medical Systems Inc., Salt Lake City, UT, USA) and a pulsed X-ray generator (DHF-155HII with Cineradiography option, Hitachi Medical Corporation, Tokyo, Japan). Participants were instructed to inhale and exhale as fully as possible after tidal breathing. The X-ray exposure conditions were the same as previously reported [20]: tube voltage, 100 kV; tube current, 50 mA; pulse duration of pulsed X-ray, 1.6 ms; source-to-image distance, 2 m; additional filter, 0.5 mm Al + 0.1 mm Cu for filtering out soft X-rays; pixel size, 388 × 388 μm; matrix size, 1024 × 768; overall image area, 40 × 30 cm. The gray-level range of the images was 16,384 (14 bits), and the signal intensity was proportional to the incident exposure of the X-ray detector. The dynamic image data, captured at 15 frames/s, were synchronized with the pulsed X-ray, which prevented excessive radiation exposure to the subjects. The exposure time was approximately 17–37 s. The entrance surface dose was approximately 0.3–1.0 mGy.

2.3. Image analysis

The measurement method is shown in Fig. 2, and an example of dynamic chest radiography is shown in Supplementary Video 1. The

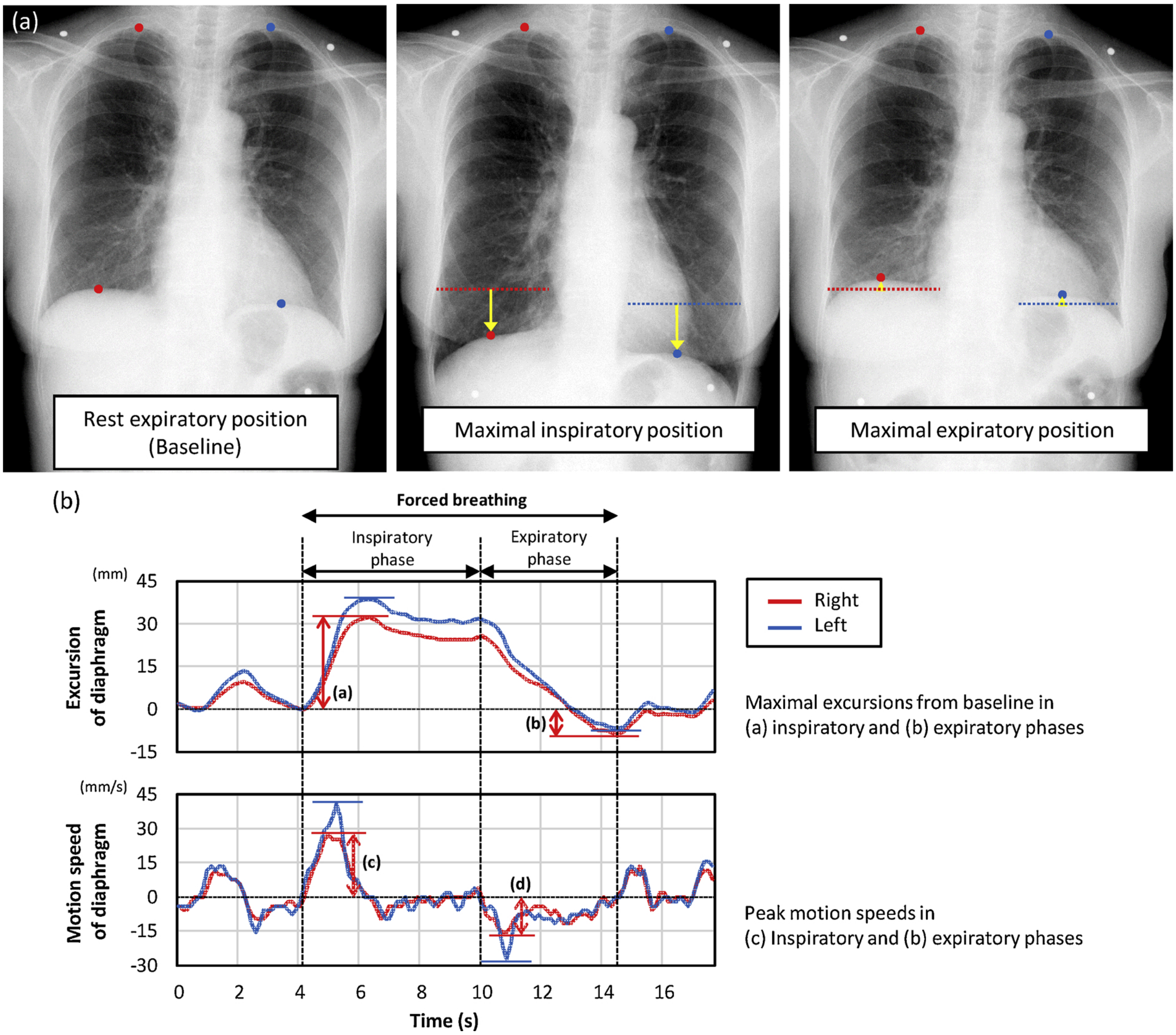

Fig. 2. An example of analysis of dynamic chest radiography. (a) Chest radiographs at rest expiratory (left), maximal inspiratory (center), and maximal expiratory (right) positions. The highest points of the diaphragms and the points of apexes were automatically set and tracked using the template-matching technique throughout the respiratory phase (right, red dots; left, blue dots) (Supplementary video 1). The positions of diaphragms in the rest expiratory phase were defined as the baseline positions (right, red dot lines; left, blue dot lines). Excursions of the diaphragms were evaluated based on the baseline positions (yellow arrows) (b) Graphs of excursions (top) and motion speeds (bottom) of the diaphragms. The motion speeds of the diaphragms were calculated by the differential method.

diaphragmatic motions on sequential chest radiographs during forced breathing were analyzed using prototype software (Konica Minolta Inc., Tokyo, Japan) installed in an independent workstation (Operating system: Windows 7 Professional 64-bit Service Pack 1; Microsoft, Redmond WA; CPU: Intel® Core™ i5-6500, 3.20 GHz; random access memory, 16 GB). The edges of the diaphragms on each dynamic chest radiograph were automatically determined by edge detection using a Prewitt Filter. The highest points of the bilateral diaphragm were automatically tracked by the template-matching technique throughout the respiratory phase, and the vertical excursions of the bilateral diaphragm were calculated. The baseline positions of the diaphragms were defined as the positions at the end of the expiratory phase of tidal breathing just before forced inspiration. Baseline positions, maximal inspiratory positions, and maximal expiratory positions from the top of the images of the bilateral diaphragms were recorded. The beginnings of inspiratory and expiratory phases were set at the time when the motion speed of the diaphragm changed from negative to positive just before the peak motion speed of inspiration, and from positive to negative just before the peak motion speed of expiration, respectively. The motion speed of each diaphragm during forced breathing was calculated based on the position and time by the differential method.

2.4. Statistical analysis

Demographic data, the results of pulmonary function tests, and diaphragmatic motion analysis were summarized as descriptive statistics values of mean ± standard deviation for continuous variables and frequency and percentages for nominal variables. Continuous variables were height, weight, BMI, tidal volume (TV), vital capacity (VC, %VC), forced expiratory volume (FEV1, FEV1%, and %FEV1), and nominal variables were gender and smoking history. A paired *t* test was performed to compare the parameters between right and left diaphragmatic motion. The association between the parameters of diaphragmatic motion, pulmonary function test results, and demographic data was analyzed using Pearson's correlation for continuous variables and Student's *t* test for nominal variables. The variables that showed statistically significant association with parameters of diaphragmatic motion by univariate analysis were assessed by multiple linear regression. Statistical analyses were performed using R version 3.5.0 software (R Foundation for Statistical Computing, Vienna, Austria). All P values were two-sided and $P < 0.05$ was considered statistically significant.

Table 1
Demographics and pulmonary function of the study population.

Characteristic	All subjects (n = 174)	
	Mean ± SD [Range] or n (%)	
Age (years)	56.8 ± 10.4	[36–93]
Sex		
Male	99	(56.9)
Female	75	(43.1)
Height (cm)	163.1 ± 8.8	[137.9–189.9]
Weight (kg)	60.7 ± 11.1	[37.0–111.8]
BMI (kg/m^2)	22.7 ± 3.1	[15.1–37.7]
Smoking history		
Current or former	56	(32.2)
Never	118	(67.8)
Pulmonary function test		
TV (L)	0.75 ± 0.35	[0.22–1.90]
VC (L)	3.37 ± 0.84	[1.24–6.91]
%VC (%)	108.0 ± 16.0	[46.7–159.6]
FEV_1 (L)	2.66 ± 0.67	[1.06–5.04]
FEV_1% (%)	80.7 ± 6.3	[57.3–97.3]
%FEV_1 (%)	104.5 ± 15.1	[55.1–163.9]

BMI, body mass index; BSA, body surface area; FEV, forced expiratory volume; SD, standard deviation; TV, tidal volume; VC, vital capacity.

3. Results

3.1. Demographics, pulmonary function tests and analysis of diaphragmatic motion

Demographic data and the results of pulmonary function tests are summarized in Table 1. This study included 99 males and 75 females (ratio, 1 : 0.76). Fifty-six out of 174 participants had a smoking history (49 males and 7 females). Seven participants showed < 80% of %VC (vital capacity/predicted vital capacity), and 10 participants showed < 70% of FEV_1% (forced expiratory volume in one second/ forced vital capacity) in this cohort.

The analysis of diaphragmatic motion measured using dynamic chest radiography is summarized in Table 2. The excursion of the left diaphragm was significantly larger than that of the right diaphragm (mean difference [MD], 2.99; 95% confidence interval [CI], 1.73–4.24; $P < 0.001$), and the ratio of right/left excursion was 0.94 ± 0.19. In the inspiratory phase, the maximal position of the left diaphragm top from the baseline was significantly larger than the right diaphragm (MD 8.02, 95% CI 6.86–9.18, $P < 0.001$). In the expiratory phase, however, it was significantly smaller (MD −4.66; 95% CI −5.47 to 3.86, $P < 0.001$). Peak distance from the apex to the diaphragm top was larger on the left side than the right side (MD 16.65; 95% CI 15.01–18.29; $P < 0.001$), while the percentage of the excursion to the apex-diaphragm distance showed no significant difference between both sides (MD −0.31; 95% CI −0.84 to 0.21; $P = 0.239$). Peak motion speeds of the left diaphragm were faster than those of the right diaphragm in both phases (inspiratory: MD 5.57, 95% CI 4.15–7.00, $P < 0.001$; expiratory: MD 2.25, 95% CI 0.88–3.63, $P = 0.001$).

3.2. Associations between excursions of the diaphragms and demographics or results of pulmonary function tests

The result of statistical analysis for associations between excursions of the diaphragms and demographics or results of pulmonary function tests is summarized in Table 3 (scatter charts are shown in Supplementary Figs. 1 and 2). Anthropometric measurements including height, weight, and BMI showed weak to moderate positive correlation with whole excursions of bilateral diaphragms (Height: right, r = 0.26; left, r = 0.35. Weight: right, r = 0.34; left, r = 0.39. BMI: right, r = 0.24; left, r = 0.24) and maximal inspiratory positions from baseline (Height: right, r = 0.18; left, r = 0.29. Weight: right, r = 0.44; left, r = 0.48. BMI: right, r = 0.44; left, r = 0.40), whereas only greater height was weakly associated with greater maximal expiratory positions from the baseline (right, r = 0.21; left, r = 0.22). Male gender was weakly associated with greater whole excursions and maximal inspiratory positions (Whole: right, r = 0.22; left, r = 0.28. Inspiratory: right, r = 0.28; left, r = 0.36).

For pulmonary function tests, excursions showed weak to moderate positive correlation with VC (Whole: right, r = 0.31; left, r = 0.41. Inspiratory: right, r = 0.22; left, r = 0.33. Expiratory: right, r = 0.25; left, r = 0.25) and FEV_1 (Whole: right, r = 0.27; left, r = 0.38. Inspiratory: right, r = 0.19; left, r = 0.30. Expiratory: right, r = 0.21; left, r = 0.24). %VC tended to be associated with whole excursions and maximal expiratory positions of the bilateral diaphragm (Whole: right, r = 0.17; left, r = 0.25. Expiratory: right, r = 0.20; left, r = 0.23). The other parameters, including age, smoking history, TV, FEV_1%, and %FEV_1 showed no significant association with the excursions of the diaphragms.

We performed multiple linear regression analysis using BMI, gender, VC, and FEV_1, taking into account the results of univariate analysis and correlation among variables (ie, height, weight, and BMI; VC and %VC; FEV_1, FEV_1%, and %FEV_1) [20]. The results are shown in Table 4. In this model, higher BMI and larger VC were significantly associated with increased whole excursions of the bilateral diaphragm (BMI: right, $P = 0.004$; left, $P = 0.009$. VC: right, $P = 0.016$; left, $P = 0.046$). In the inspiratory phase, higher BMI and male gender showed a significant association with increased excursions in the bilateral and the left, respectively (BMI: right, $P < 0.001$; left, $P < 0.001$. Gender: left, $P = 0.047$). In the expiratory phase, larger VC showed a significant association with the increased excursion of the right diaphragm ($P = 0.032$).

3.3. Associations between peak motion speeds of the diaphragms and demographics or results of pulmonary function tests

The results of statistical analysis for associations between peak motion speeds of the diaphragms and demographics or results of

Table 2
Statistics of Diaphragmatic Motions of the Study Population.

	Right diaphragm Mean ± SD [Range]	Left diaphragm Mean ± SD [Range]	*P* value
Whole excursion (mm)	49.1 ± 17.0 [11.6–96.5]	52.1 ± 15.9 [20.8–95.1]	< 0.001**
Maximal inspiratory position from baseline (mm)	28.9 ± 10.7 [7.1–62.1]	36.9 ± 12.3 [12.2–71.7]	< 0.001**
Maximal expiratory position from baseline (mm)	20.7 ± 12.2 [0–58.6]	16.1 ± 10.1 [0.4–56.0]	< 0.001**
Ratio of right/left excursion	0.94 ± 0.19 [0.46-1.82]		–
Peak distance of apex-diaphragm (mm)	238.4 ± 21.9 [142.8–294.6]	255.1 ± 23.1 [173.8–320.4]	< 0.001**
Excursion/apex-diaphragm distance (%)	22.4 ± 7.1 [5.7–41.7]	22.1 ± 6.0 [8.8–40.2]	0.239
Peak motion speed in inspiratory phase (mm/s)	26.7 ± 10.0 [9.7–50.4]	32.2 ± 12.4 [11.6–97.0]	< 0.001**
Peak motion speed in expiratory phase (mm/s)	22.1 ± 12.7 [7.8–108.6]	24.3 ± 10.3 [7.8–66.0]	0.001**

Subjects, n = 174; ** indicates $P < 0.01$.; SD, standard deviation.

Table 3
Associations between excursions of the diaphragms and participant demographics or results of pulmonary function tests by univariate analysis.

	Right		Left	
	r or Effect Size [95% CI]	*P* value	r or Effect Size [95% CI]	*P* value
Whole Excursion of the Diaphragm				
Age	−0.09 [−0.24, 0.06]	0.218	−0.06 [−0.21, 0.09]	0.405
Height	0.26 [0.11, 0.39]	< 0.001**	0.35 [0.21, 0.47]	< 0.001**
Weight	0.34 [0.20, 0.47]	< 0.001**	0.39 [0.26, 0.51]	< 0.001**
BMI	0.24 [0.10, 0.38]	0.001**	0.24 [0.09, 0.37]	0.001**
TV	0.13 [−0.01, 0.28]	0.079	0.15 [−0.003, 0.29]	0.054
VC	0.31 [0.17, 0.44]	< 0.001**	0.41 [0.27, 0.52]	< 0.001**
%VC	0.17 [0.02, 0.31]	0.027*	0.25 [0.11, 0.39]	< 0.001**
FEV_1	0.27 [0.12, 0.40]	< 0.001**	0.38 [0.24, 0.50]	< 0.001**
FEV_1%	−0.06 [−0.21, 0.09]	0.398	−0.03 [−0.18, 0.11]	0.656
%FEV_1	0.03 [−0.12, 0.17]	0.735	0.15 [0.004, 0.29]	0.044*
Gender (Male)	0.22 [0.08, 0.36]	0.003**	0.28 [0.13, 0.41]	< 0.001**
Smoking history	0.01 [−0.13, 0.16]	0.857	−0.00 [−0.15, 0.15]	0.998
Maximal Inspiratory Position from Baseline				
Age	−0.06 [−0.21, 0.09]	0.401	−0.02 [−0.12, 0.17]	0.748
Height	0.18 [0.03, 0.32]	0.017*	0.29 [0.14, 0.42]	< 0.001**
Weight	0.44 [0.31, 0.55]	< 0.001**	0.48 [0.35, 0.58]	< 0.001**
BMI	0.44 [0.31, 0.55]	< 0.001**	0.40 [0.27, 0.52]	< 0.001**
TV	0.14 [−0.01, 0.28]	0.070	0.13 [−0.02, 0.26]	0.081
VC	0.22 [0.08, 0.36]	0.003**	0.33 [0.20, 0.46]	< 0.001**
%VC	0.03 [−0.12, 0.17]	0.740	0.13 [−0.02, 0.27]	0.093
FEV_1	0.19 [0.04, 0.33]	0.013*	0.30 [0.16, 0.43]	< 0.001**
FEV_1%	−0.08 [−0.23, 0.06]	0.265	−0.07 [−0.22, 0.07]	0.326
%FEV_1	−0.03 [−0.17, 0.12]	0.743	0.12 [−0.03, 0.27]	0.104
Gender (Male)	0.28 [0.14, 0.42]	< 0.001**	0.36 [0.22, 0.49]	< 0.001**
Smoking history	0.12 [−0.02, 0.27]	0.100	0.07 [−0.08, 0.22]	0.339
Maximal Expiratory Position from Baseline				
Age	−0.06 [−0.21, 0.09]	0.440	−0.10 [−0.24, 0.05]	0.194
Height	0.21 [0.06, 0.35]	0.006**	0.22 [0.07, 0.36]	0.004**
Weight	0.11 [−0.04, 0.26]	0.135	0.08 [−0.07, 0.23]	0.277
BMI	−0.02 [−0.17, 0.13]	0.805	−0.06 [−0.21, 0.08]	0.396
TV	0.05 [−0.10, 0.20]	0.488	0.05 [−0.10, 0.19]	0.548
VC	0.25 [0.10, 0.38]	0.001**	0.25 [0.11, 0.39]	< 0.001**
%VC	0.20 [0.05, 0.34]	0.008**	0.23 [0.09, 0.37]	0.002**
FEV_1	0.21 [0.06, 0.35]	0.006**	0.26 [0.09, 0.37]	0.002**
FEV_1%	−0.02 [−0.17, 0.13]	0.807	−0.02 [−0.13, 0.17]	0.786
%FEV_1	0.06 [−0.09, 0.21]	0.441	0.09 [−0.06, 0.23]	0.252
Gender (Male)	0.09 [−0.06, 0.23]	0.243	0.05 [−0.09, 0.20]	0.484
Smoking history	−0.06 [−0.21, 0.09]	0.411	−0.02 [−0.17, 0.13]	0.804

P values and correlation coefficients (r) were calculated using Pearson's correlation for continuous variables. *P* values and effect sizes were calculated using Student's *t* test for nominal variables. * indicates $P < 0.05$; ** indicates $P < 0.01$; BMI, body mass index; CI, confidence interval; FEV, forced expiratory volume; VC vital capacity; TV, tidal volume.

pulmonary function tests is summarized in Table 5 (scatter charts are shown in Supplementary Figs. 1 and 2). Higher weight and BMI tended to be associated with higher peak motion speeds in both inspiratory and expiratory phases (Weight, inspiratory: right, r = 0.25; left: r = 0.22. Weight, expiratory: right, r = 0.21; left, r = 0.29. BMI, inspiratory: right, r = 0.21; left, r = 0.17. BMI, expiratory, right, r = 0.19; left, r = 0.22). The other parameters including age, height, gender, and smoking history showed no significant association with the peak motion speeds of the diaphragms.

For the pulmonary function tests, VC, %VC, FEV_1, and %FEV_1 were weakly associated with the peak motion speed of the left diaphragm in the inspiratory phase (VC, r = 0.23; %VC, r = 0.21; FEV_1, r = 0.20; %FEV_1, r = 0.20). The peak motion speeds of the bilateral diaphragm in the expiratory phase showed no significant correlation with the parameters of the pulmonary function tests.

In the multiple linear regression analysis model using BMI, gender, VC, and FEV_1, higher BMI showed significant association with the peak motion speeds of both diaphragms in the expiratory phase (right, P = 0.020; left, P = 0.010). In the inspiratory phase, BMI and VC were significantly associated with the peak motion speed of the right and the left diaphragms, respectively (BMI: right, P = 0.016. VC: left, P = 0.048) (Table 4).

4. Discussion

This is the first report assessing diaphragmatic motion in a standing position during forced breathing in a health screening cohort using dynamic chest radiography. We analyzed the positions of the top of the diaphragms on dynamic chest radiography sequentially and provided objective and quantitative data of excursions and motion speeds of the diaphragms. We also demonstrated the characteristics and laterality of the diaphragmatic motion in the inspiratory and expiratory phases. The maximal expiratory position from baseline was greater in the right than the left during forced breathing, whereas the whole excursion was greater in the left; this difference of laterality in diaphragmatic motion may partly result from restriction by other anatomical structures such as the liver and the heart. Quantitative evaluation of diaphragmatic kinetics can play an important role in management and treatment of diaphragmatic dysfunction states caused by respiratory diseases, post operation of respiratory organs, and respiratory rehabilitation. Dynamic chest radiography provides objective and repeatedly acquirable data of diaphragmatic kinetics and can be a useful imaging

Table 4
Associations between excursions of the diaphragms and participant demographics or results of pulmonary function tests by multiple linear regression analysis.

	Right			Left		
	Coef	SE	*P* value	Coef	SE	*P* value
Whole Excursion						
Intercept	4.074	10.258	0.691	6.418	9.293	0.491
BMI	1.153	0.399	0.004**	0.953	0.362	0.009**
Gender	−0.068	3.071	0.982	0.474	2.785	0.865
VC	10.645	4.365	0.016*	7.958	3.958	0.046*
FEV_1	−6.402	5.151	0.216	−1.162	4.672	0.803
Maximal Inspiratory Position						
Intercept	−7.547	6.144	0.221	−5.160	6.887	0.455
BMI	1.368	0.239	< 0.001**	1.340	0.268	< 0.001**
Gender	2.879	1.841	0.120	4.138	2.064	0.047*
VC	3.428	2.617	0.192	4.091	2.933	0.165
FEV_1	−2.936	3.089	0.343	−1.691	3.462	0.626
Maximal Expiratory Position						
Intercept	10.748	7.673	0.163	9.730	6.308	0.125
BMI	−0.140	0.299	0.641	−0.254	0.246	0.302
Gender	−2.103	2.300	0.362	−2.565	1.890	0.177
VC	7.077	3.268	0.032*	4.345	2.687	0.108
FEV_1	−3.588	3.857	0.354	−0.417	3.171	0.896
Peak Motion Speed in Inspiratory Phase						
Intercept	8.638	6.328	0.174	7.661	7.757	0.325
BMI	0.600	0.246	0.016*	0.595	0.302	0.050
Gender	1.469	1.896	0.440	−1.451	2.324	0.533
VC	3.115	2.695	0.249	6.590	3.304	0.048*
FEV_1	−2.608	3.181	0.413	−3.889	3.900	0.320
Peak Motion Speed in Expiratory Phase						
Intercept	−0.815	8.076	0.920	4.873	6.522	0.456
BMI	0.737	0.314	0.020*	0.659	0.254	0.010*
Gender	−0.581	2.420	0.811	1.198	1.954	0.541
VC	4.040	3.440	0.242	1.218	2.778	0.662
FEV_1	−2.681	4.060	0.510	−0.108	3.278	0.974

*Indicates $P < 0.05$; ** indicates $P < 0.01$; BMI, body mass index; Coef, coefficient; FEV, forced expiratory volume; VC vital capacity; SE, standard error.

modality for assessment of the diaphragm along with fluoroscopy, US, CT, and MRI.

Several studies have reported the average excursions of the diaphragms, but the results are not consistent, and may vary depending on modalities, postures, and breathing method [4,8,9,12,16]. Boussuges et al. used US to analyze 195 healthy subjects deep breathing in a standing position and reported mean diaphragmatic excursions of 6.6 cm (right diaphragm) and 7.3 cm (left diaphragm) [8]; in this study using dynamic chest radiography we observed smaller values of 4.9 cm and 5.2 cm, respectively. Boussuges et al. also analyzed tidal breathing with US, and reported average excursions of 1.8 cm right and 1.8 cm left; Yamada et al. reported smaller average excursions of 1.1 cm right and 1.5 cm left [20] measured using dynamic chest radiography. This variance of the average values may be caused by differences in not only modalities, but also demographics and instructions for breathing. Further studies are needed to clarify the reasons for the disparities and establish standard values for diaphragmatic motion.

The association between the diaphragmatic motion and the pulmonary function was weak to moderate, consistent with the Boussuges et al. study using US, reported that the diaphragmatic excursion during deep breathing mildly correlated with VC and FEV_1 in a healthy cohort [8]. Diaphragmatic motion is only one of the factors affecting pulmonary function, and this mild correlation is understandable. This study also demonstrates the association between anthropometric measurements and diaphragmatic motion, especially that higher BMI correlates with larger excursions and higher peak motion speeds of the diaphragms. Our results agree with previous studies reporting the association between BMI and diaphragm excursions using US in forced breathing [12], and dynamic chest radiography in tidal breathing [20]. We assessed our cohort with stratification by BMI into normal (18.0–24.9 kg/m^2) and overweight (> 25 kg/m^2), and the diaphragmatic motions of overweight subjects were larger in the inspiratory phase and smaller in the expiratory phase compared to normal weight subjects (Supplementary Table 1). This discrepancy may be caused by a shift of the baseline and expiratory positions of the diaphragms in

Table 5
Associations between peak motion speeds of the diaphragms and participant demographics or results of pulmonary function tests by univariate analysis.

	Right		Left	
	r or Effect Size [95% CI]	*P* value	r or Effect Size [95% CI]	*P* value
Inspiratory Phase				
Age	−0.01 [−0.16, 0.13]	0.850	0.06 [−0.09, 0.21]	0.442
Height	0.13 [−0.02, 0.28]	0.078	0.15 [0.003, 0.29]	0.045*
Weight	0.25 [0.10, 0.38]	< 0.001**	0.22 [0.08, 0.36]	0.003**
BMI	0.21 [0.07, 0.35]	0.005**	0.17 [0.02, 0.31]	0.029*
TV	0.05 [−0.10, 0.20]	0.505	0.02 [−0.13, 0.17]	0.801
VC	0.16 [0.01, 0.30]	0.032*	0.23 [0.09, 0.37]	0.002**
%VC	0.04 [−0.10, 0.19]	0.567	0.21 [0.07, 0.35]	0.004**
FEV_1	0.13 [−0.02, 0.27]	0.086	0.20 [0.05, 0.36]	0.009**
FEV_1%	−0.04 [−0.19, 0.10]	0.558	−0.06 [−0.21, 0.09]	0.408
%FEV_1	0.01 [−0.14, 0.15]	0.940	0.20 [0.05, 0.34]	0.009**
Gender (Male)	0.18 [0.03, 0.32]	0.020*	0.13 [−0.02, 0.27]	0.091
Smoking history	0.08 [−0.06, 0.23]	0.267	−0.07 [−0.22, 0.07]	0.329
Expiratory Phase				
Age	0.001 [−0.15, 0.15]	0.980	0.03 [−0.12, 0.18]	0.673
Height	0.10 [−0.05, 0.24]	0.201	0.18 [0.03, 0.32]	0.017*
Weight	0.21 [0.06, 0.35]	0.006**	0.29 [0.15, 0.42]	< 0.001**
BMI	0.19 [0.04, 0.33]	0.012*	0.22 [0.08, 0.36]	0.003**
TV	−0.004 [−0.15, 0.14]	0.960	0.12 [−0.03, 0.26]	0.114
VC	0.14 [−0.005, 0.29]	0.060	0.15 [0.003, 0.29]	0.046*
%VC	0.11 [−0.04, 0.26]	0.135	0.04 [−0.11, 0.19]	0.564
FEV_1	0.12 [−0.03, 0.26]	0.116	0.14 [−0.008, 0.28]	0.063
FEV_1%	−0.04 [−0.18, 0.11]	0.637	0.01 [−0.14, 0.16]	0.883
%FEV_1	0.07 [−0.08, 0.22]	0.360	0.06 [−0.09, 0.21]	0.446
Gender (Male)	0.10 [−0.05, 0.24]	0.184	0.16 [0.01, 0.30]	0.038*
Smoking history	0.08 [−0.07, 0.22]	0.317	−0.02 [−0.17, 0.12]	0.748

P values and correlation coefficients (r) were calculated using Pearson's correlation for continuous variables. *P* values and effect sizes were calculated using Student's *t* test for nominal variables. * indicates $P < 0.05$; ** indicates $P < 0.01$. BMI, body mass index; CI, confidence interval; FEV, forced expiratory volume; VC vital capacity; TV, tidal volume.

overweight subjects owing to abdominal components. Moreover, overweight subjects showed a smaller distance of apex-diaphragm than normal despite larger excursions, and this disproportion may result in respiratory discomfort in overweight subjects. We need to consider the influence of BMI in diaphragmatic motion assessment.

Our study has several limitations. First, this study included 174 volunteers from a single institute, and additional studies with larger and multicenter cohorts are needed to confirm our observations. Second, we only evaluated the movement of the top of the diaphragms in posteroanterior view. We believe this one-dimensional analysis is simple, practical, and easily applicable for clinical use, but we have to note it does not necessarily represent the whole function of the diaphragm, which has three-dimensional structure and motion. Previous reports have revealed that COPD patients may show heterogeneous and/or paradoxical diaphragmatic movement during ventilation on dynamic MRI [23,24]. The influence of the heterogeneous and/or paradoxical motion may not be described in this study with only posteroanterior view. Third, this study was based on the data from one cycle of forced breathing in each participant. Although we confirmed the condition of each participants' respiration was proper for analysis, an assessment with multicycle or repeated examination of each participant is preferable in order to exclude the possibility of improper respiration.

In conclusion, we demonstrated the characteristics of diaphragmatic motion during forced breathing in a health screening cohort using dynamic chest phrenicography. The analysis of diaphragmatic motion is important for the assessment of respiratory function and provides an indicator for management of patients who have respiratory difficulty with such conditions as COPD, post operation issues, and respiratory rehabilitation. The excursions and peak motion speeds of the diaphragms may be affected by anthropometric measurements including BMI.

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Conflict of interest

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Appendix A. Supplementary data

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