Breathing Pattern and Chest Wall Kinematics during Phonation in Chronic Obstructive Pulmonary Disease Patients

B. Binazzi^a B. Lanini^a F. Gigliotti^a G. Scano^{a, b}

^aSection of Respiratory Rehabilitation, Don C. Gnocchi ONLUS-IRCCS Foundation, and ^bSection of Allergology and Clinical Immunology, Department of Internal Medicine, University of Florence, Florence, Italy

Key Words

Operational volumes · Optoelectronic plethysmography · Speech

Abstract

Background: Breathing pattern description and chest wall kinematics during phonation have not been studied in male and female patients with chronic obstructive pulmonary disease. **Objectives:** We used optoelectronic plethysmography to provide a quantitative description of breathing pattern and chest wall kinematics. **Methods:** Volumes of chest wall compartments (rib cage and abdomen) were assessed in 15 patients while reading aloud (R), singing (SI) and during high-effort whispering (HW). **Results:** Relative to quiet breathing, tidal volume and expiratory time increased while inspiratory time decreased. The expiratory flow decreased during R and SI, but was unchanged during HW. In males, the end-expiratory volume decreased as a result of a decreased volume of rib cage during R, SI and HW and due to a decreased volume of abdomen during HW. In females, a decrease in end-expiratory volume was accomplished by a decrease in abdominal volume during R and HW. During R, the chest wall end-expiratory volume of the last expiration in females was to the left of the maximal expiratory flow volume

curve (MEFV), with still substantial expiratory reserve volume available. In contrast, during SI and HW in females and during all types of phonation in males, chest wall end-expiratory volume of the last expiration was well to the right of the MEFV curve and associated with respiratory discomfort. Gender had a greater importance than physical characteristics in determining more costal breathing in females than in males under all conditions studied. **Conclusions:** Phonation imposes more abdominal breathing pattern changes in males and costal changes in females. Expiratory flow encroaches upon the MEFV curve with higher phonatory efforts and respiratory discomfort.

Copyright © 2013 S. Karger AG, Basel

Introduction

The pattern of breathing during speech consists of long expiration at a low flow rate and flow reserve and quick interspersed inspiration [1, 2]. Phonation imposes a more complex organization, recruitment of and burden on expiratory muscles [1]. Physical characteristics dictate the contribution of chest wall compartments (i.e. upper rib cage, lower rib cage and abdomen) to the difference in expired volume in healthy male and female subjects [2].

Table 1. Anthropometric and lung function data in male and female COPD patients

	Age years	Height m	BMI kg/m ²	TLC liter	FRC liter	FEV ₁ liter	FVC liter	FEV ₁ /FVC %	VC liter	ERV liter
Males										
Mean	71	1.71	25.99	6.99 (109)	4.67 (132)	1.57 (56)	2.99 (82)	52	3.38 (89)	1.05 (78)
SD	8	0.05	4.40	0.82 (16)	0.75 (23)	0.63 (21)	0.62 (14)	15	0.68 (16)	0.37 (27)
Females										
Mean	69	1.51	25.04	4.57 (110)	2.98 (122)	1.01 (64)	1.99 (102)	50	2.27 (119)	0.75 (87)
SD	8	0.04	3.26	0.43 (12)	0.45 (16)	0.33 (27)	0.39 (27)	8	0.36 (27)	0.32 (25)

Figures in parentheses are percent predicted values. BMI = Body mass index; TLC = total lung capacity; FEV₁ = forced expiratory volume in 1 s; FVC = forced VC.

The assessment of ventilatory constraints and related sensory perceptions during speech activities may provide relevant measurement criteria for patients with limited physical activities who use oral communication for most social activities [3].

The chest wall plays a central role in maintaining ventilation. However, to the best of our knowledge, breathing pattern description and chest wall kinematics during phonation have not been studied in male and female patients with chronic obstructive pulmonary disease (COPD). Whether physical characteristics or gender per se dictate the breathing patterns during phonation in these patients has yet to be defined. The hyperinflation of the rib cage and abdomen in tandem represents the mechanical constraints to volume displacement in these patients [4]. However, deflationary activity of the abdominal compartment might not be able to reduce constraints on chest wall expiratory volume displacement if the rib cage is being dynamically hyperinflated. In turn, chest wall compartments can contribute in varying ways to expiration in these patients.

We are well aware that no data have been published on gender differences on chest wall hyperinflation in patients with COPD. However, data from our laboratory suggest a prevailing contribution of the rib cage to chest wall hyperinflation in female patients. On this basis, we hypothesized that, unlike data in healthy subjects, gender rather than physical characteristics dictates the pattern of breathing during phonation in patients with COPD.

The main aims of this study were to assess whether different chest wall characteristics are associated with different phonation in patients with COPD. To achieve this aim, we have used optoelectronic plethysmography (OEP) to assess breathing during three types of phona-

tion: reading aloud (R), singing (SI) and high-effort whispering (HW) which requires greater flows and volume excursion than normal reading or singing.

Material and Methods

Study Design

All patients were well acquainted with the experimental protocol and equipment used. They were tested in the morning after lung function measurements. All optoelectronic measurements of chest wall motion were made with patients sitting upright in a comfortable armchair. The measurements were made initially during quiet breathing (QB) and then during R, SI and HW. The QB signals were recorded over a 3-min period after a 10-min period of adaptation to equipment. The chosen phonatory task was reading, singing or whispering the first two strophes of the Italian version of the popular Christmas carol 'O Christmas Tree', which consists of 4 verses and 127 syllables. The number of syllables per verse was relatively constant, ranging from 14 to 17. All patients were familiar with the song. Each patient listened to the verses once and then repeated each phonatory task three times. The last performance was chosen for each analysis. Each patient read aloud at his or her own chosen intensity level, while HW was performed with the highest possible effort. Singing was standardized in rhythm and tonality by making the experimental patients sing together. Reading, singing and whispering were linguistically constrained because the same words were used during these activities.

During QB and the various phonatory tasks, volume and time components of the breathing pattern were assessed, as previously described [2].

Methods

We studied 15 clinically stable patients with COPD (9 men; table 1). Five patients were hyperinflated [functional residual capacity (FRC) range 135–186% of the predicted value] and had varying degrees of airway obstruction [forced expiratory volume in 1 s/forced vital capacity (VC), and forced expiratory volume in 1 s]. None had abnormalities of the vertebral column nor defects of phonation or hearing. None of the patients was a professional

or amateur singer nor had received voice training. On the day of testing, they were free from allergies, infections or colds. The study was approved by the local ethics committee and the subjects gave their informed consent.

Routine spirometry was measured according to the American Thoracic Society/European Respiratory Society guidelines [5]. FRC was measured with a body plethysmograph (Autobox DL 6200; SensorMedics, Yorba Linda, Calif., USA), according to a standardized procedure [6]. The normal values for lung function were those of the European Community for Coal and Steel [7]. The anthropometric and lung function data of the patients are given in table 1.

Measurements obtained with OEP have been previously described in detail and validated [8–11]. In brief, the coordinates of 89 markers were tracked by six infrared charge-coupled TV cameras (three cameras were 4 m in front of and three were 4 m behind the subject) at a sampling rate of 60 Hz (fig. 1). Starting from the marker co-ordinates, the thoracoabdominal volumes were computed by triangulating the surface.

Analysis

OEP calculates absolute volumes, and those of each compartment at FRC in control conditions were considered the reference volume. Volumes are reported as absolute values and as changes from the volume at FRC in control conditions. The chest wall volume (V_{cw}) was modeled as the sum of the volume of the rib cage apposed to the lung ($V_{rc,p}$), the volume of the rib cage apposed to the abdomen ($V_{rc,a}$) and the abdominal volume (V_{ab}). Expiratory time (T_E) was the main outcome of the study. Post hoc statistical power was >90% for all the three experimental conditions (96, 98 and 99% for HW vs. QB, R vs. QB and SI vs. QB, respectively).

Values are means $\pm$ SD unless otherwise specified. A nonparametric statistical procedure was used to test gender differences (Mann-Whitney test). The breathing patterns during the various study conditions were compared using two-way ANOVA. The Duncan test was used for multiple comparisons. The level of significance was set at $p \leq 0.05$. All statistical procedures were carried out using the Statgraphics Plus 5.1 statistical package (Statistical Graphics Corp., USA).

Results

The study was carried out from January 2010 to January 2012.

Figure 2 shows the changes in V_{cw} during R, SI and HW in a representative patient. In all instances, the breaths consisted of a rapid inspiration with a slower expiration performed with essentially constant flow. Since the expired tidal volumes (V_{TE}) were generally greater than the inspired tidal volumes (V_{TI}), the end-expiratory V_{cw} ($V_{cw,ee}$) decreased progressively during each phonetic sequence. The end-inspiratory V_{cw} ($V_{cw,ei}$) also decreased. Similar results were found in all patients though the timing and magnitude of the changes in $V_{cw,ei}$ and $V_{cw,ee}$ were variable.

Fig. 1. Experimental setup.

Breathing Pattern

The average breathing pattern of the 15 patients under various conditions is shown in table 2 and schematized in online supplementary figure E1 (for all online suppl. material, see www.karger.com/doi/10.1159/000346027). Compared with QB, during phonation, V_{TI} and V_{TE} were greater, the inspiratory time (T_I) was shorter and the expiratory time (T_E) longer, with a concurrent increase in V_{TI}/T_I . V_{TI} and V_{TI}/T_I were especially high during HW (Duncan test, $p < 0.01$ to $p < 0.00001$). Neither V_{TE}/T_E nor frequency (f) changed significantly during HW. In contrast, V_{TE}/T_E and frequency decreased during SI ($p < 0.03$ and $p < 0.01$). In general, R and SI showed large changes in timing ($p < 0.00001$ for both) and driving ($p < 0.001$ and $p < 0.0001$, respectively).

Comparison among phonatory tasks showed no difference between R and SI, while HW showed greater volumes compared to R (Duncan test: V_{TI} , $p = 0.03$; V_{TE} , $p = 0.04$; $V_{TI} \cdot f$, $p = 0.03$), and lower T_E ($p = 0.03$); greater V_{TE}/T_E ($p = 0.0001$), $T_I/\text{total time}$ ($p = 0.04$), and $V_{TI} \cdot f$ ($p = 0.01$) when compared to SI. Gender differences in breathing pattern normalized for VC were as follows: in males, T_I and T_E were shorter during QB ($p = 0.04$ and 0.009 , respectively), V_{TE}/T_E was higher during

Table 2. Breathing patterns of 15 COPD patients under various conditions

	VTi, liter	VTE, liter	Ti, s	TE, s	Ti/TTOT	VTi/Ti, l s ⁻¹	VTE/TE l s ⁻¹	Frequency min ⁻¹	VTi • f l min ⁻¹
QB	0.50±0.13	0.50±0.13	1.13±0.25	1.72±0.49	0.40±0.04	0.48±0.2	0.34±0.21	22.5±7	11.7±6.3
R	0.57±0.15	0.64±0.23	0.59±0.11	2.81±0.92	0.19±0.06	1.04±0.36	0.25±0.08	19±6.1	10.6±2.6
SI	0.65±0.27	0.67±0.29	0.62±0.11	3.27±0.95	0.17±0.04	1.15±0.47	0.21±0.07	16.6±4.8	10±3
HW	0.78±0.31	0.85±0.36	0.66±0.16	2.55±0.72	0.21±0.06	1.22±0.45	0.36±0.13	19.8±4.8	14.7±5.4
ANOVA									
F	3.65	4.21	29	8.95	60.49	10.52	3.72	2.49	2.88
p	0.019	0.0101	0.0000	0.0001	0.0000	0.0000	0.0174	0.0715	0.0456

TTOT = Total time; Ti/TTOT = duty cycle; VTi/Ti = mean inspiratory flow; VTE/TE = expiratory flow; VTi • f = inspired minute ventilation.

R ($p = 0.001$), and VTi • f was higher during R and SI ($p = 0.003$ and 0.04 , respectively).

V_{cw,ei} and V_{cw,ee}

Table 3 provides the values of V_{cw} (%VC) during phonatory tasks relative to QB before utterance. During all types of phonation, V_{cw,ee} of the last expiration (V_{cw,eeL}) decreased [see the negative values of V_{cw,eeL}–V_{cw,eeQB} (V_{cw,ee} during QB)] similarly in males and in females. V_{cw,ei} of the starting inspiration (V_{cw,eiS}) did not change during phonation in either gender; however, it was higher and its difference from V_{cw,eeQB} was larger during HW in females than in males.

Figure 3 depicts the average expiratory flow volume ($\dot{V}$ -V) relationships during the different types of phonation in relation to the corresponding maximal expiratory flow-volume (MEFV) curves of males and females. The latter were obtained by ensemble averaging the individual MEFV curves obtained with the body plethysmograph in the 9 males (fig. 3, left panel) and 6 females (fig. 3, right panel). Only the portion of the MEFV curves for $\dot{V} \leq 1$ liter s⁻¹ is shown. The horizontal lines depict the mean values of expiratory flow (corresponding to VTE/TE in table 2) from V_{cw,eiS} to V_{cw,eeL}. During R, the V_{cw,eeL} of females was to the left of the MEFV curve, i.e. there was still substantial expiratory reserve volume (ERV) available. In contrast, during SI and HW in females and during all types of phonation in males, the V_{cw,eeL} was well to the right of the MEFV curve and associated with unpleasant respiratory sensations or fatigue. It should be noted that the values of V_{cw,eeL} showed substantial interpatient variability in both males and females (table 3). Also, the V_{cw,eeL} did not correlate with baseline ERV during phonation (online suppl. fig. E2).

Fig. 2. Changes in V_{cw} during R with a normal voice (top), SI (middle) and HW (bottom) the two strophes of the Christmas carol in a representative patient. Open circles = V_{cw,eiS}; filled circles = V_{cw,eeL}.

Fig. 3. Mean expiratory flow-volume relationships of males (left) and females (right) during R, SI and HW, with corresponding MEFV curves. The flow-volume relationships encompass the V_{eIS} and the V_{eEL} , obtained during the phonetic tasks. Total lung capacity (TLC), FRC and residual volume (RV) are expressed as %VC. FVC = Forced VC.

Table 3. Change in V_{cw} during different types of phonation

	R		SI		HW	
	males	females	males	females	males	females
$V_{cw,eIQB}$, %VC	48±12	53±15	48±12	53±15	48±12	53±15
$V_{cw,eeQB}$, %VC	31±10	34±13	31±10	34±13	31±10	34±13
$V_{cw,eIS}$, %VC	48±12	48±19	51±16	59±24	45±12	61±18*
$V_{cw,eeL}$, %VC	7±22	20±21	14±14 [§]	27±10	2±13 [§]	21±16
$V_{cw,eIS}-V_{cw,eeQB}$, %VC	17±9	14±10	20±14	22±13	14±9	27±13*, [†]
$V_{cw,eeL}-V_{cw,eeQB}$, %VC	-24±27	-14±12	-17±12	-7±9	-29±12	-12±12

* $p \leq 0.05$ compared to males; [†] $p \leq 0.05$ compared to R; [§] $p \leq 0.05$ compared to $V_{cw,eeQB}$.

Kinematics

The compartment values of both $V_{cw,eIS}$ and $V_{cw,eeL}$ during phonation relative to QB are depicted in figure 4. There was a chest wall decrease in end-expiratory volume for all types of phonation in males (fig. 4, left panels), with significant reductions in $V_{cw,eeL}$ which was allocated to the upper rib cage during R, SI and HW and to the abdomen during HW. A decrease in $V_{ab,eeL}$ during phonation resulted in decreased $V_{cw,eeL}$ during R and HW in females (fig. 4, right panels). The absolute values of the last end-expiratory volume (V_{eEL}) and the starting end-

inspiratory volume (V_{eIS})- V_{eEL} in males were generally higher than in females, probably reflecting the gender differences in size (table 1).

The average contribution of the three chest wall compartments to $V_{cw,ee}$ are shown in table 4. The contribution of $V_{rc,p}$ (%VTE), $V_{rc,a}$ (%VTE) and V_{ab} (%VTE) to $V_{cw,ee}$ did not change ($p = 0.94$, $F = 0.12$; $p = 0.97$, $F = 0.08$, and $p = 0.93$, $F = 0.13$, respectively) during phonation. Nonetheless, in all instances, the contribution of the abdomen was smaller in females than in males. In contrast, the contributions of $V_{rc,p}$ (during QB and R) and

Fig. 4. Average V_{eIS} (open symbols) and V_{eEL} (filled symbols) of the chest wall (V_{cw}) and its three compartments ($V_{rc,p}$, $V_{rc,a}$ and V_{ab}) during QB, R, SI and HW in males (circles) and females (triangles). All volumes are shown in relation to end-expiratory volume during QB. Bars = 1 SD; dashed line = FRC. * $p \leq 0.05$ relative to QB.

$V_{rc,a}$ (during QB, R and SI) were higher in females, while no gender difference in terms of RC contribution was found during HW.

Figure 5 depicts the average ($\pm$ SD) relationships of V_{cw} , $V_{rc,p}$ and $V_{rc,a}$ to V_{ab} relative to those of the end-inspiratory volume of the start inspiration and the end-expiratory volume of the last expiration (i.e. volume changes between open and closed circles in fig. 1) dur-

ing QB and phonation in males (fig. 5, left panels) and females (fig. 5, right panels). The slope ($\Delta V_x/\Delta V_{ab}$, where x is the chest wall or relevant chest wall compartment) of $\Delta V_{cw}/\Delta V_{ab}$ tended to be the same for all phonatory tasks in both genders. By contrast, the decrease in V_{ab} was larger than the decrease in V_{rc} in males, whereas the decrease in V_{rc} was larger than that in V_{ab} in females.

Fig. 5. Average relationships of V_{cw} , $V_{rc,p}$ and $V_{rc,a}$ versus V_{ab} at end-inspiration (open symbols) and end-expiration (filled symbols) during QB (circles), R (triangles), SI (hexagons) and HW (squares) of males (left panels) and females (right panels).

Finally, neither V_{ab} (%VTE) nor V_{rc} (%VTE) were correlated with VC (liters) (see online suppl. fig. E3).

Discussion

This is the first study which assesses the breathing pattern during speech in COPD patients. The novel findings of this study are as follows: (1) patients modified their

breathing pattern relative to QB with all types of phonation; (2) breathing was more abdominal in males during all phonatory tasks, but more costal during QB, R and SI in females; (3) $V_{cw,ei}$ was not significantly different from QB during phonation; (4) respiratory difficulty occurred when $V_{cw,ee}$ impinged on the MEFV curve during HW and SI, and (5) little or no chest wall distortion was found during phonation in either gender.

Table 4. Volume changes of three thoracic compartments during QB and different phonatory tasks

	Vrc,p, %VTE			Vrc,a, %VTE			Vab, %VTE		
	males	females	p	males	females	p	males	females	p
QB	32±6	41±7	0.03	14±6	25±13	0.05	55±11	34±17	0.02
R	32±6	43±10	0.03	12±6	18±17	0.33	55±6	39±18	0.03
SI	30±11	38±10	0.18	14±5	24±15	0.11	56±10	38±19	0.04
HW	32±7	41±14	0.13	17±6	22±10	0.31	51±11	37±10	0.04

Breathing Pattern

In an earlier systematic study of breathing during phonation conducted in a group of normal young men and women, Binazzi et al. [2] provided a quantitative description of breathing pattern and chest wall kinematics during R, SI and HW of two strophes of a popular Christmas carol for the first time. They found no significant gender-related differences in breathing pattern during QB and various phonatory tasks when tidal volumes were normalized for VC. On the other hand, in the present study, we found gender differences in breathing pattern, when normalized for VC, as follows: T_I and T_E were shorter during QB, VTE/T_E was higher during R, and VT_I • f was higher during R and SI in males (fig. 3). Whether different afferent information from lung and/or chest wall, airway geometry or other mechanical abnormalities dictated gender differences during phonation remains to be defined.

Operational Volumes

V_{cw,eeL} decreased (see the negative values of V_{cw,eeL}-V_{cw,eeQB}) in males as well as in females (table 3) in all phonatory tasks. In addition, V_{cw,eeL}, end-expiratory V_{rc,p} and V_{rc,a} of the last expiration were associated with a larger decrease in end-expiratory V_{ab} of the last expiration in males compared to females. In contrast, a decrease in V_{cw,eeL} was accomplished by a greater decrease in end-expiratory V_{rc,p} and V_{rc,a} of the last expiration in females. V_{cw,eis} did not change during phonation in each compartment and in either gender, but was higher at HW in females.

The V_{cw} early in inspiration is accomplished by relaxation of abdominal muscles which contribute to chest wall tidal volume [9, 10]. As shown here (fig. 4), the null increment of end-inspiratory V_{rc} and V_{ab} limits the contribution of inspiratory muscles to chest wall VT. This kinematic pattern was more evident during HW when end-inspiratory abdominal VT, as an expression of de-

scent of the diaphragm [9, 10], tended to be the lowest in males and females.

Phonation is associated with longer expiration and larger volume excursion [1] with lung deflation being accomplished by a decrease in V_{cw,eeL} as an index of substantial respiratory muscle tension [9]. During maximal phonatory tasks, V_{cw,eeL} closely approaches the MEFV curves, and the flow required for speech can no longer be sustained because the maximal flows decrease along the MEFV curve [2]. This explains the need for larger ERV and flow reserve for phonation. While healthy subjects can maintain an average airflow rate not above 0.5 l/s [12], severely obstructed patients may experience difficulty as they are flow limited even at rest [13, 14]. These patients often break speech phrases, probably because they can maintain a flow rate only at higher lung volumes. The progressive expiratory muscle tension results in dynamic airway compression, distortion and collapse that can stimulate upper airway receptors to initiate vagal afferent impulses that contribute to dyspnea [15]. Figure 3 depicts the average $\dot{V}$ -V relationship exhibited during phonation by males and females with the corresponding MEFV curve. During SI and HW in females and during all types of phonation in males, the V_{cw,eeL} was well to the right of the MEFV curve and associated with unpleasant respiratory sensations or fatigue. So, the finding that expiratory flow decreased, regardless of phonatory tasks, suggests a similar expiratory effort or a similar level of attained flow, limiting critical pressure during phonation. When V_{cw,ee} and the MEFV curve intersect, the flow required can no longer be sustained because the maximal flow decreases along the MEFV curve. This emphasizes the importance of expiratory flow reserve and ERV for phonation. However, as shown here, V_{cw,eeL} during phonation did not correlate with baseline ERV. This is in contrast with the finding in healthy subjects that the higher the baseline ERV, the greater the reduction in V_{cw,ee} during phonation [2]. Although the reasons for this dis-

crepancy are likely to be complex, the following should be considered. While on the one hand OEP measures gas volumes, thoracic gas compression and blood shift from the thorax to the extremities, on the other hand, errors of measurement with the pneumotachograph may result in spurious increments or decrements in volume measurements. Thus, spirometric measurements, especially expiratory, may not correlate with OEP measurements in patients with varying levels of gas compression and/or blood shifting. Also, the substantial interpatient variability of $V_{cw,ee}$ in both males and females (table 3) might play a role.

Chest Wall Kinematics

During phonation, the rib cage and abdomen contributed to the decrease in $V_{cw,ee}$ in males and females, respectively. When expressed as percentage of expired V_{TE} , breathing was generally more abdominal in males and more costal during QB, R and SI in females (fig. 4, 5; table 4). This was unrelated to the difference in size as shown by lack of a significant correlation between V_{ab} expressed as percentage of expired tidal volume and VC expressed in liters. This finding contrasts with the observation in healthy subjects [2] in whom physical characteristics have greater importance than gender in determining the breathing pattern and chest wall kinematics during phonation.

Rib Cage Distortion

The coordinated action of operating respiratory muscles during exercise explains the low rib cage distortion in healthy subjects [9, 16, 17]. Conversely, nonuniformly distributed pressure on the rib cage, or different values of upper and lower rib cage compliance [18], might account for constant upper to lower rib cage uncoupling throughout exercise. Unlike paradoxical movements of the lower rib cage at rest [19], during arm exercise [4] or during whole body endurance exercise [20], the minimal or null RC distortion during phonatory tasks might be better explained by coordinated activity of the respiratory muscles [17].

In conclusion, phonation imposes changes in the breathing pattern more abdominal in males and costal in females. Expiratory flow encroaches upon the MEFV curve during higher phonatory efforts, thus engendering the perception of respiratory discomfort.

Acknowledgement

The authors are grateful to Prof. Joseph Milic-Emili for his suggestions and criticisms. This paper was supported by a grant from the Don C. Gnocchi ONLUS (IRCCS) Foundation and the Ministero dell'Università e della Ricerca Scientifica e Tecnologica of Italy.

References

- 1 Estenne M, Zocchi L: Speech; in Roussos C (ed): *The Thorax*. New York, Dekker, 1995, pp 1315–1333.
- 2 Binazzi B, Lanini B, Bianchi R, Romagnoli I, Nerini M, Gigliotti F, Duranti R, Milic-Emili J, Scano G: Breathing pattern and kinematics in normal subjects during speech, singing and loud whispering. *Acta Physiol (Oxf)* 2006; 186:233–246.
- 3 Binazzi B, Lanini B, Romagnoli I, Garuglieri S, Stendardi L, Bianchi R, Gigliotti F, Scano G: Dyspnea during speech in chronic obstructive pulmonary disease patients: effects of pulmonary rehabilitation. *Respiration* 2011;81:379–385.
- 4 Romagnoli I, Gigliotti F, Lanini B, Bruni GI, Coli C, Binazzi B, Stendardi L, Scano G: Chest wall kinematics and breathlessness during unsupported arm exercise in COPD patients. *Respir Physiol Neurobiol* 2011;178: 242–249.
- 5 Miller MR, Hankinson J, Brusasco V, Burgos F, Casaburi R, Coates A, Crapo R, Enright P, van der Grinten CPM, Gustafsson P, Jensen R, Johnson DC, Macintyre N, McKay R, Navajas D, Pedersen OF, Pellegrino R, Viegi G, Wanger J: Standardisation of spirometry. *Eur Respir J* 2005;26:319–338.
- 6 Wanger J, Clausen JL, Coates A, Pedersen OF, Brusasco V, Burgos F, Casaburi R, Crapo R, Enright P, van der Grinten CP, Gustafsson P, Hankinson J, Jensen R, Johnson D, Macintyre N, McKay R, Miller MR, Navajas D, Pellegrino R, Viegi G: Standardization of the measurement of lung volumes. *Eur Respir J* 2005; 26:511–522.
- 7 European Community for Coal and Steel: Standardization of lung function tests. *Eur Respir J* 1993;6(suppl 16):1–100.
- 8 Cala SJ, Kenyon CM, Ferrigno G, Carnevali P, Aliverti A, Pedotti A, Macklem PT, Rochester DF: Chest wall and lung volume estimation by optical reflectance motion analysis. *J Appl Physiol* 1996;81:2680–2689.
- 9 Aliverti A, Cala SJ, Duranti R, Ferrigno G, Kenyon CM, Pedotti A, Scano G, Sliwinski P, Macklem PT, Yan S: Human respiratory muscle actions and control during exercise. *J Appl Physiol* 1997;83:1256–1269.
- 10 Sanna A, Bertoli F, Misuri G, Gigliotti F, Iandelli I, Mancini M, Duranti R, Ambrosino N, Scano G: Chest wall kinematics and respiratory muscle action in walking healthy humans. *J Appl Physiol* 1999;87:938–946.
- 11 Lanini B, Bianchi R, Romagnoli I, Coli C, Binazzi B, Gigliotti F, Pizzi A, Grippo A, Scano G: Chest wall kinematics in patients with hemiplegia. *Am J Respir Crit Care Med* 2003;168: 109–113.
- 12 Bouhuys A: Voluntary breathing acts: speech, singing, and wind-instrument playing; in Bouhuys A (ed): *Breathing, Physiology, Environment and Lung Disease*. New York, Grune and Stratton, 1974, pp 234–260.

- 13 O'Donnell DE, Bertley JC, Chau LK, Webb KA: Qualitative aspects of exertional breathlessness in chronic airflow limitation: pathophysiologic mechanisms. *Am J Respir Crit Care Med* 1997;155:109–115.
- 14 O'Donnell DE, Hamilton AL, Webb KA: Sensory-mechanical relationships during high-intensity, constant-work-rate exercise in COPD. *J Appl Physiol* 2006;101:1025–1035.
- 15 Davenport PW, Reep RL: Cerebral cortex and respiration; in Dempsey JA, Pack AI (eds): *Regulation of Breathing*. New York, Dekker, 1995, pp 365–388.
- 16 Duranti R, Sanna A, Romagnoli I, Nerini M, Gigliotti F, Ambrosino N, Scano G: Walking modality affects respiratory muscle action and contribution to respiratory effort. *Pflugers Arch* 2004;448:222–230.
- 17 Kenyon CM, Cala SJ, Yan S, Aliverti A, Scano G, Duranti R, Pedotti A, Macklem PT: Rib cage mechanics during quiet breathing and exercise in humans. *J Appl Physiol* 1997;83:1242–1255.
- 18 Chihara K, Kenyon CM, Macklem PT: Human rib cage distortability. *J Appl Physiol* 1996;81:437–447.
- 19 Binazzi B, Bianchi R, Romagnoli I, Lanini B, Stendardi L, Gigliotti F, Scano G: Chest wall kinematics and Hoover's sign. *Respir Physiol Neurobiol* 2008;160:325–333.
- 20 Innocenti Bruni G, Gigliotti F, Binazzi B, Romagnoli I, Duranti R, Scano G: Dyspnea, chest wall hyperinflation, and rib cage distortion in exercising patients with chronic obstructive pulmonary disease. *Med Sci Sports Exerc* 2012;44:1049–1056.