Chest wall motion during tidal breathing

A. DE GROOTE, M. WANTIER, G. CHERON, M. ESTENNE, AND M. PAIVA
Department of Electronics, Microelectronics and Telecommunications, Laboratory of Movement Biomechanics, Chest Service, Erasme University Hospital, and Biomedical Physics Laboratory, Free University of Brussels, 1070 Brussels, Belgium

De Groote, A., M. Wantier, G. Cheron, M. Estenne, and M. Paiva. Chest wall motion during tidal breathing. *J. Appl. Physiol.* 83(5): 1531–1537, 1997.—We have used an automatic motion analyzer, the ELITE system, to study changes in chest wall configuration during resting breathing in five normal, seated subjects. Two television cameras were used to record the *x-y-z* displacements of 36 markers positioned circumferentially at the level of the third (S_1) and fifth (S_2) costal cartilage, corresponding to the lung-apposed rib cage; midway between the xyphoid process and the costal margin (S_3), corresponding to the abdomen-apposed rib cage; and at the level of the umbilicus (S_4). Recordings of different subsets of markers were made by submitting the subject to five successive rotations of 45–90°. Each recording lasted 30 s, and three-dimensional displacements of markers were analyzed with the Matlab software. At spontaneous end expiration, sections S_{1-3} were elliptical but S_4 was more circular. Tidal changes in chest wall dimensions were consistent among subjects. For S_{1-2}, changes during inspiration occurred primarily in the cranial and ventral directions and averaged 3–5 mm; displacements in the lateral direction were smaller (1–2 mm). On the other hand, changes at the level of S_4 occurred almost exclusively in the ventral direction. In addition, both compartments showed a ventral displacement of their dorsal aspect that was not accounted for by flexion of the spine. We conclude that, in normal subjects breathing at rest in the seated posture, displacements of the rib cage during inspiration are in the cranial, lateral outward, and ventral directions but that expansion of the abdomen is confined to the ventral direction.

rib cage; respiratory muscles; abdomen; mechanics; shape

SINCE THE WORK of Konno and Mead (8), the chest wall has been considered as a structure with two compartments, the rib cage and the abdomen. Distinct displacements of each part have been measured with magnetometers (9) and inductive plethysmography (Respitrace) (10), but three-dimensional (3D) motion within each compartment has not been analyzed in detail because the information provided by the Respitrace was limited to changes in a single rib cage or abdominal cross section and magnetometers did not provide simultaneous measurements for more than three or four diameters. In 1985, Ferrigno et al. (6) described a new method enabling the analysis of 3D movements of a large number of markers fixed on the chest wall. The method was validated in 12 healthy subjects in a study in which inspired volumes were computed from geometric reconstructions and were compared with spirometric data (5). In present work, we have analyzed with the same technique detailed movements of points located on the rib cage and the abdomen during quiet breathing. The aim of the study was to assess respiratory changes in the 3D configuration of the chest wall and to provide normative data for seated subjects.

MATERIALS AND METHODS

Chest wall motion was studied by using an automatic motion analyzer, the ELITE system (5). This system records the position of markers (hemispheres coated with reflective paper) placed on an object in motion by using television cameras that have different viewpoints. The system supplies the acquisition of two-dimensional frames for each camera and then computes 3D coordinates of each marker as a function of time. It also provides algorithms that filter the noisy biological signals (4, 6). In addition to these measurements, respiratory changes in rib cage and abdomen cross section were measured using inductive plethysmography.

In our experiments, the ELITE system was calibrated for a working volume of 60 cm × 60 cm × 40 cm. We estimated the resolution to be 0.1 mm by measuring the signal-to-noise ratio while the system was recording the position of a static marker. For the volume studied, the ELITE manufacturers give a precision better than ⅓ mm. We have recorded the displacements of a marker positioned with a micrometer and have calculated a precision better than ½ mm.

We studied five healthy male subjects of whom two were highly trained in respiratory maneuvers (Table 1). The subjects were studied while seated on a rotating stool with the lower portion of the dorsal spine resting against a support. They were asked to maintain the same position during the acquisitions and to breathe quietly through a pneumotachograph by using a mouthpiece and a noseclip. No particular instruction regarding the breathing pattern was given. We positioned a total of 36 (or 37) markers (Fig. 1) by using the projection of a grid on the body with a slide projector. The markers were attached around the chest wall at the level of the third (S_1) and fifth (S_2) costal cartilage, corresponding to the lung-apposed rib cage; midway between the xyphoid process and the costal margin (S_3), corresponding to the abdomen-apposed rib cage; and at the level of the umbilicus (S_4). Markers that were in front of the spine were fixed on the support. Each section, S_1, S_2, S_3, and S_4, was perpendicular to the craniocaudal axis of the body and was described by eight markers. The markers of sections S_2 and S_4 were fixed on the rib cage and abdomen Respitrace bands, respectively. Comparison between movements of the markers and changes in rib cage and abdominal cross section will form the basis of another study.

Because our Elite system included only two television cameras, we recorded motion of different subsets of markers during six successive acquisitions. Between two acquisitions, the orientation of the subject relative to the cameras was modified by rotating the stool (Fig. 2) [angle of rotation (α) = 0, 45, 135, 180, 225, and 315°]. Data were recorded at a rate of 50 Hz during periods of 30 s. When movements of the ventral part of the body were recorded (α = 0, 45, and 315°), the subjects' hands were positioned behind the back. When movements of the dorsal part of the body were recorded (α = 135, 180, and 225°), the hands were placed on the knees (Fig. 1).

Table 1. *Physical characteristics of subjects*

Subject	Age, yr	Height, m	Weight, kg
MP	52	1.72	70
NP	29	1.86	77
OV	25	1.76	70
VA	39	1.77	65
WP	28	1.76	56
Mean ± SD	34.60 ± 9.89	1.77 ± 0.05	67.6 ± 6.95

Flow at the mouth was recorded with a Lilly-type pneumotachograph and a Validyne differential pressure transducer. Volume was obtained by flow integration, and calibration was made by means of a 1-liter syringe. The flow signal was recorded on an eight-channel tape recorder, digitized at a frequency of 50 Hz with an analog-digital card, and synchronized with the ELITE data.

Data analysis. The Matlab software was used to analyze data. This software package is a technical computing environment for high-performance numeric computation and visualization. It was first necessary to merge the sets of ELITE measurements obtained in different orientations of the body. Accordingly, for each recording done in the relative axis system $x'y'z'$ of the cameras (Fig. 2), we applied a rotation (α) around its origin (o′) to express data in an intermediate system. This system was parallel to the absolute system xyz of the subject ($\alpha = 0°$) but did not share the same origin (o and o′ in Fig. 2). Therefore we chose the marker placed on the support as the characteristic point in each system, and we made a translation (t) to merge the origins of the two systems. For some acquisitions, the position of this characteristic marker had been actually recorded (α = 135, 180, and 225°), but for others (α = 0, 45, and 315°), it was located by using the position of the marker placed on the sternum and the distance between this marker and the one placed on the support.

For the 3D analysis of movements, we defined y (craniocaudal), z (dorsoventral), and x (laterolateral) components, and we considered that movements were positive in sign when oriented in the cranial, ventral, and lateral outward directions. Projections were made on axial (horizontal), coronal (frontal), and sagittal (lateral) planes (Fig. 1). For all available breaths in each subject, we selected data that belonged to the interval [(mean tidal volume) × 0.8, (mean tidal volume) × 1.2]. This allowed us to obtain a reasonable breath-by-breath variability during the successive acquisitions and to discard shallow or deep breaths. We computed the mean position of the markers at the beginning and end of the selected inspirations, which defined the tidal vector.

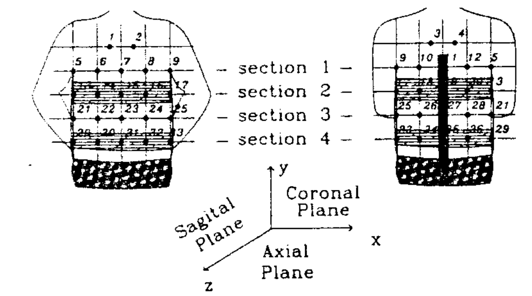


Fig. 1. Schematic view of ventral and dorsal aspects of the chest wall in 1 subject showing positioning of markers (●), Respitrace bands (hatched areas), and spine support. x, y, and z, Laterolateral, craniocaudal, and dorsoventral axes, respectively.

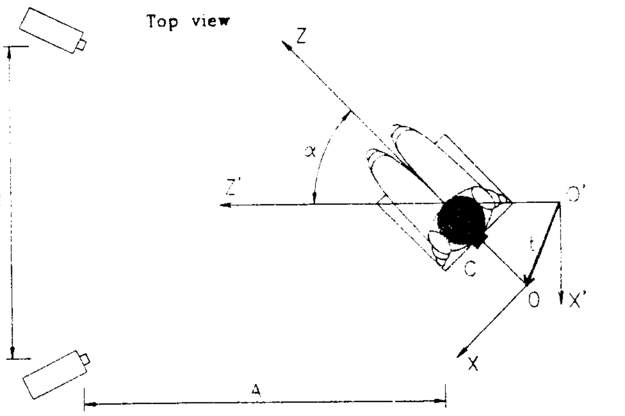


Fig. 2. Schematic view of subject positioned on rotating stool with his spine resting on a support (C). Cameras were placed 150 cm (A) from the subject and were spaced 128 cm (B) apart. $x'y'z'$, Relative axis system with respect to cameras; α, angle of rotation between absolute axis system xyz and $x'y'z'$; t, translation vector between the 2 axis systems; o and o′, origins.

Two t-tests were performed on the tidal vectors in the x, y, and z directions. The first one was done to evaluate whether the mean of the movements of one marker in a given subject was significantly different from zero. The second one was done on each set of five individual means to determine whether movements of one marker in the five subjects were significantly different from zero. We also compared the sign of individual means with the sign of group means for each marker.

RESULTS

Configuration at end expiration. We show in Fig. 3*A* (section S_1) and Fig. 3*B* (section S_3), for one representative subject (*VA*) at end expiration, the mean position of the markers (axial projection) recorded from each viewpoint. Although double points were sometimes visible, data recorded from different viewpoints were consistent.

Respiratory movements during tidal breathing. Figure 4*A* (section S_1, axial projection) and Fig. 4*B* (sections S_1–S_4, frontal projection) show for one representative subject (*VA*) the positions of the markers at the beginning and at the end of selected inspirations. The tidal vector is amplified by a factor of 10. The orthogonal scale refers to the anthropometric dimensions of the body, and the 3-mm scale refers to the amplitude of respiratory movements. Figure 4 illustrates that, although obtained during successive acquisitions with the subject in different orientations, the position of the markers did not show too much scatter.

To study the variability in amplitude and direction of tidal vectors between subjects, we represented all vectors in Figs. 5, *A–D*, and 6; in Figs. 5 and 6, tidal vectors from all subjects were merged to have the same origin. The scales are the same as in Fig. 4. We observed that markers on the rib cage (Fig. 5, *A*, *B*, *C*: S_1, S_2, S_3, respectively) moved mainly in the ventral and cranial direction during inspiration. Lateral movements were small for all markers and, as expected, were negligible for markers positioned on the mediosagittal line (navel, sternum). For the abdomen (Fig. 5*D*: S_4), the largest movements were in the ventral direction. Lateral and craniocaudal movements were small. The navel did not present any lateral movement. Markers placed on the support did not move. Finally, markers on the dorsal aspect of the rib cage and abdomen presented movements that predominated in the ventral direction.

Table 2 summarizes average displacements of the seven markers of sections S_2 and S_4 and of the two markers fixed on the support. It also provides information relative to individual trends and level of statistical significance for group data. We considered separately the markers placed on the mediosagittal line and on the ventral, lateral, or dorsal portions of the chest. Changes in the left and right side of the body were averaged. Table 2 also gives the number of respirations used for each measurement. We observed that displacements of the ventral and lateral parts of the rib cage during inspiration occurred primarily in the cranial and ventral directions and averaged 3–5 mm. Displacements in the lateral outward direction were smaller (1–2 mm). For the abdomen, displacements predominated in the ventral direction and were more pronounced for the ventral part. The dorsal parts of the rib cage and

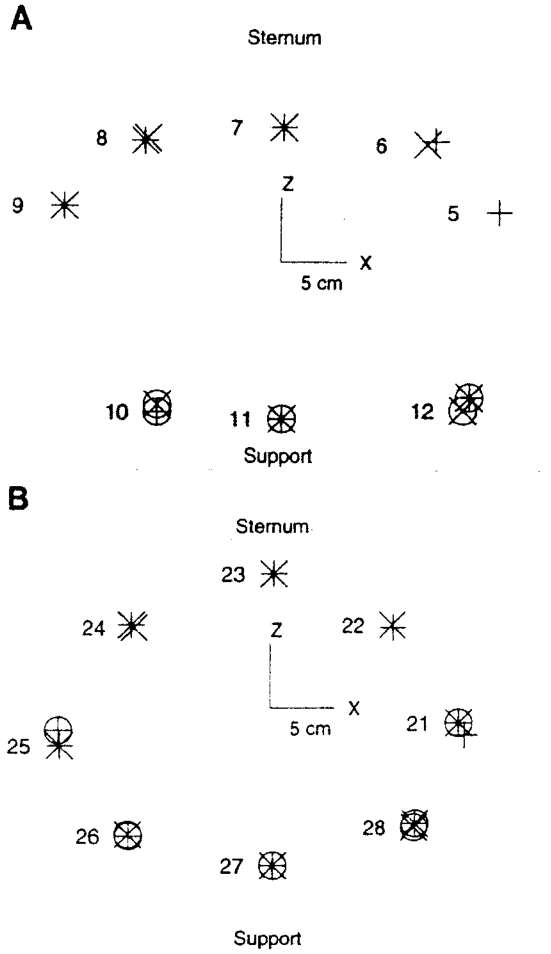


Fig. 3. Shapes of 2 cross sections in *subject VA* after data obtained from different viewpoints were merged. (*A*: S_1, *B*: S_3). x, data obtained for $\alpha = 0°$; *, data for $\alpha = 45°$; ⊕, data for $\alpha = 135°$, ⊗, data for $\alpha = 180°$; encircled crossed plus, data for $\alpha = 225°$; +, data for 315°.

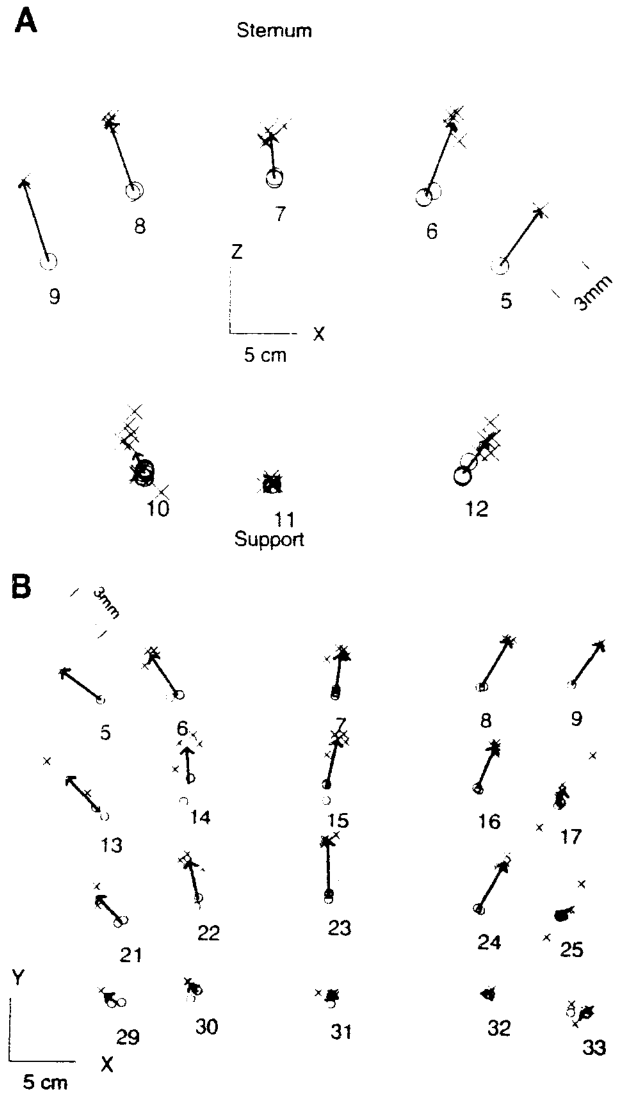


Fig. 4. Movements of markers (*subject VA*) in axial plane for section S_1 (*A*) and in coronal plane for ventral aspect of chest wall (*B*). ○, Beginning of inspiration; X, end of inspiration; arrows = mean tidal vectors. See text for discussion.

abdomen also showed significant movements, in particular in the ventral direction.

DISCUSSION

Assessment of the method. We assumed that the spine, which rested against a fixed and rigid support, was motionless. This assumption was verified by a specific experiment described in the APPENDIX. To reconstruct the 3D movements of the chest wall, it was necessary to perform successive measurements from different viewpoints. This explains why multiple points were sometimes visible for the same marker recorded during successive acquisitions (Figs. 3 and 4) and why movements of markers placed symmetrically on the left and right part of the chest wall were not always identical. Furthermore the angle (α) that describes the orientation of the subject with respect to the cameras was measured by reference to a mark on the stool with a precision of ~3°. Taking into account that the angle of

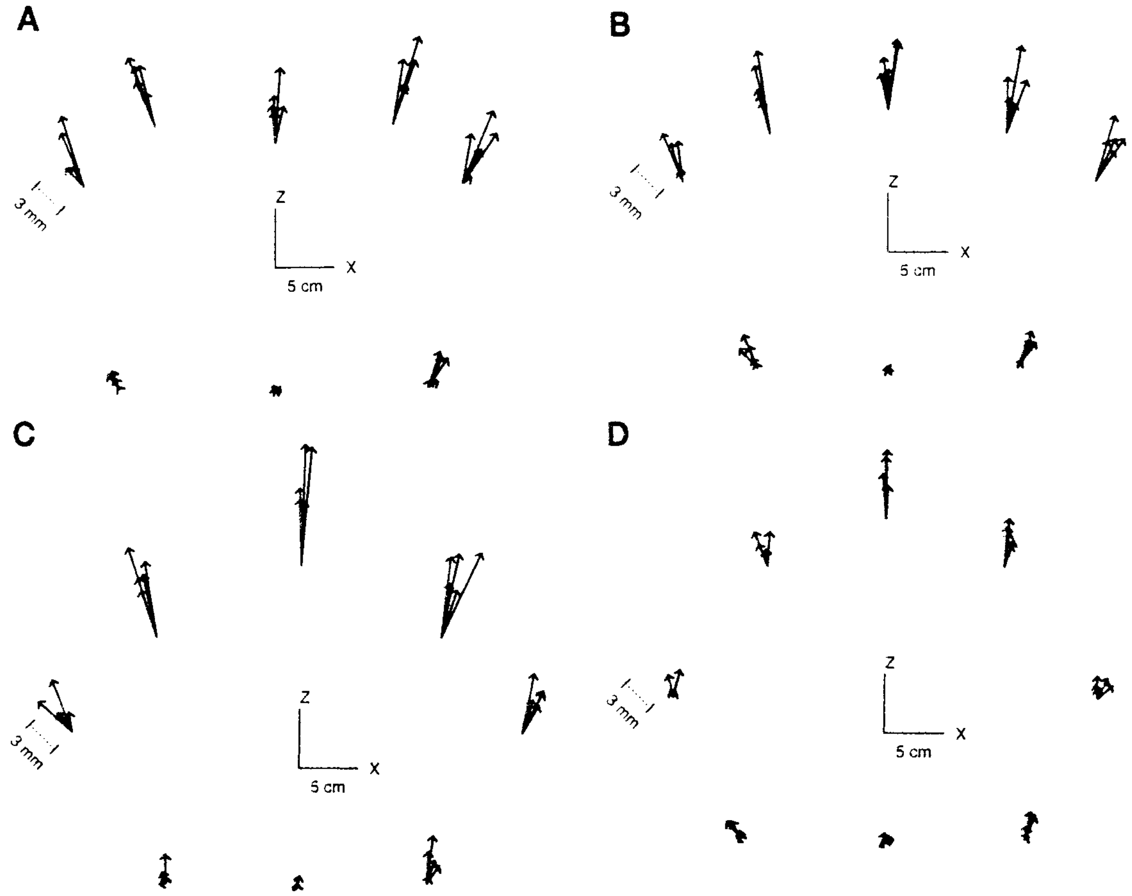


Fig. 5. Mean tidal vectors for all subjects shown in axial plane for sections S_1 (*A*), S_2 (*B*), S_3 (*C*), and S_4 (*D*).

the subject could slightly differ from the angle of the stool, we estimated that the global precision was 5°. Finally, to visualize lateral markers, we had to make measurements with the arms either on the knees or behind the back. This postural change could also be responsible for small modifications in marker position. Results shown in Fig. 3 suggest, however, that the errors of the method were small.

Configuration at end expiration. It is shown in Fig. 3 for *subject VA* that, at end expiration, the ratio between the dorsoventral and transverse diameters was smaller for the rib cage than for the abdomen. A similar observation was made in the other subjects, indicating that, in the seated posture, the abdominal cross section is closer to a circle than the rib cage cross section. This finding is consistent with previous studies of chest wall

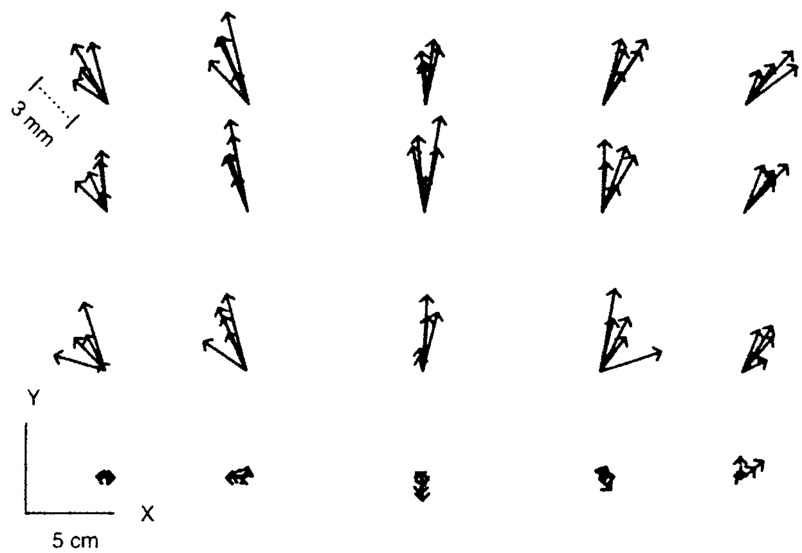


Fig. 6. Mean tidal vectors (coronal projection) for all subjects shown for markers attached to ventral aspect of the chest wall.

le 2. *Average chest wall displacements during tidal breathing*

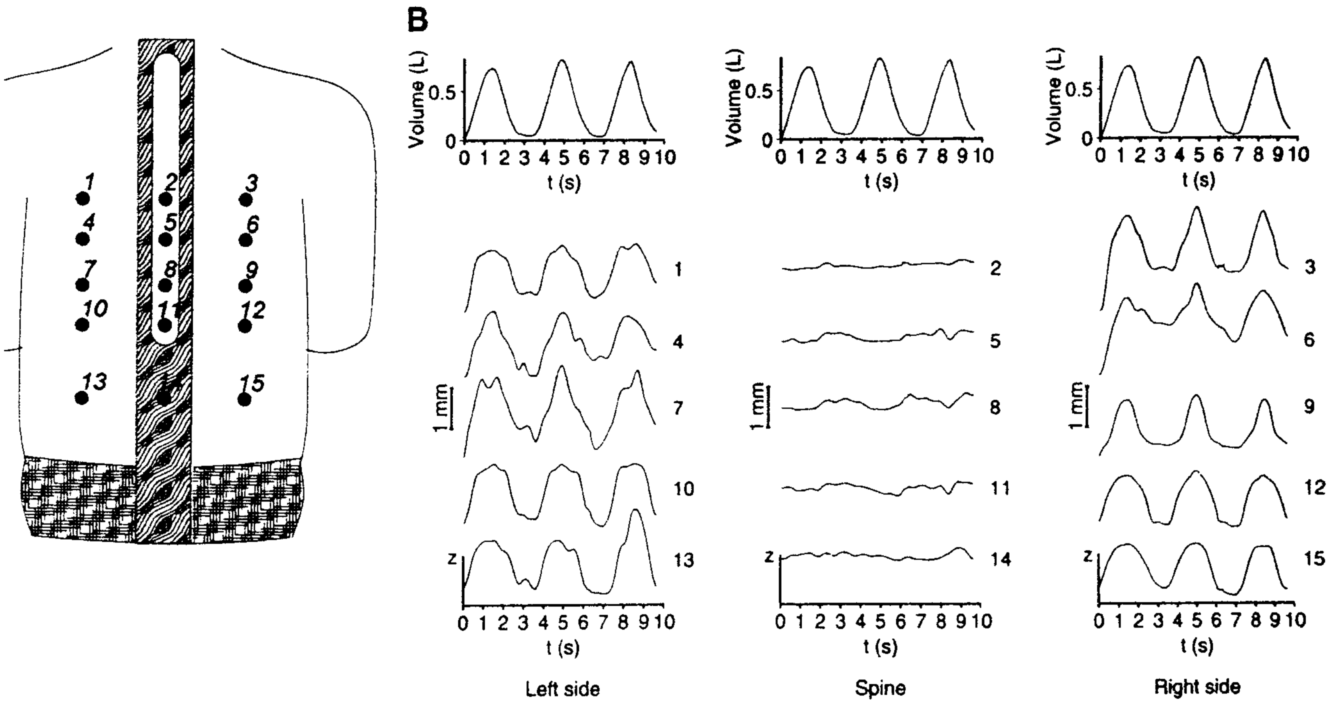
	n	Craniocaudal Motion		Laterolateral Motion		Dorsoventral Motion	
		Mean, mm	d, e, f	Mean, mm	d, e, f	Mean, mm	d, e, f
Rib cage							
Sternum (15)	55	3.71[c]	5, 0, 0	−0.11		4.33[c]	5, 0, 0
Ventral part (14, 16)	74	3.15[c]	5, 0, 0	0.97[c]	5, 0, 0	4.23[c]	5, 0, 0
Lateral part (13, 17)	50	2.15[c]	5, 0, 0	1.21[c]	4, 1, 0	2.96[c]	4, 1, 0
Dorsal part (18, 20)	75	0.68[c]	4, 1, 0	0.91[c]	4, 1, 0	1.71[c]	5, 0, 0
Abdomen							
Navel (31)	55	−0.39[a]	3, 0, 2	0.03		4.03[c]	5, 0, 0
Ventral part (30, 32)	74	0.14[a]	3, 1, 1	0.47[c]	4, 1, 0	2.39[c]	5, 0, 0
Lateral part (29, 33)	61	0.53[b]	4, 1, 0	0.19[a]	1, 4, 0	1.14[c]	4, 1, 0
Dorsal part (34, 36)	75	0.6[b]	4, 1, 0	0.54[b]	4, 1, 0	1.13[c]	5, 0, 0
Support (19, 35)	100	0.05		0		0.14[a]	2, 3, 0

erage values for tidal displacements of markers (marker nos. are within parentheses) in 5 normal subjects studied; n, no. of respirations. ements are positive in sign when oriented in the cranial, ventral, and lateral outward directions. [a]$P < 0.01$; $0.01 <$ [b]$P < 0.05$; [c]$P > 0.05$ (by). When the mean amplitude was <0.1 mm, no statistical analysis was performed. Results of individual t-tests: [d]no. of subjects for whom idual test was significant ($P<0.05$) and mean was of same sign as group mean; [e]no. of subjects for whom individual test was not ficant ($P>0.05$); [f]individual test was significant but sign of individual mean was opposite to sign of group mean.

pe obtained by using magnetometers in normal mans (13).

Respiratory movements during tidal breathing. Mea-ements of rib cage and abdominal dimensions have a previously obtained by Konno and Mead (8) using rs of linear differential transducers and by Wade and Agostoni et al. (2) using mercury-in-rubber nsducers. They studied how the dorsoventral and nsverse diameters or the circumference of the rib e and abdomen changed during various respiratory neuvers in the upright and/or the supine posture (1). The present study, geometric displacements of sev- markers fixed on the chest wall were measured h the subjects in the seated posture and during quiet breathing. This study differs from earlier works in that the 3D displacement of each marker was computed, which allowed us to assess changes in the 3D configuration of the chest wall during breathing.

We found that the pattern of marker displacements during tidal breathing was similar in the five subjects of the study. The rib cage was invariably displaced in the cranial direction during inspiration and showed an outward motion of its ventral and lateral aspects. Based on the anatomy of the ribs' articulations with the vertebral bodies, cranial motion of a rib is expected to be accompanied by a ventral and a lateral component, but the amplitude of these two components should differ in the upper vs. the lower portion of the rib cage.



7. *A*: schematic view of dorsal aspect of chest wall in 1 subject showing positioning of markers (●) and ated support used during specific experiment performed to study movements of spine (APPENDIX). *B*: lung e and dorsoventral movements for markers (nos. 1–15) are shown as a function of time.

In the upper portion of the cage, the rib neck axes are almost parallel to the frontal plane of the body. Consequently, when the upper ribs move cranially in inspiration, their ventral ends move ventrally but their lateral displacement is small (the so-called "pump-handle" motion). In contrast, the axes of the necks of the lower ribs are oriented dorsally. Therefore, elevation of these ribs in inspiration is accompanied by a significant lateral expansion (the so-called "bucket-handle" motion) (11, 12, 15). In the present study, we did not find such a difference between the upper and lower portions of the rib cage; as shown in Fig. 5, *A–C*, there was no clear-cut difference in the relative amplitude of the ventral and lateral displacements measured at the level of the third costal cartilage (S_1) and midway between the xyphoid process and the costal margin (S_3). This observation can be best explained by the fact that the orientation of the rib neck axes changes significantly between *ribs 1–2* and *3–4* but is very similar for all ribs located caudally to *ribs 3–4* (7).

In contrast to the rib cage, markers placed on the abdomen did not show any cranial motion during inspiration, and lateral movements were small. In fact, motion of the ventral and lateral aspects of the abdominal wall was primarily in the ventral direction such that the abdomen became more circular during inspiration. This deformation can be explained by the fact that skeletal structures constrain the abdomen laterally and restrict its lateral expansion during breathing.

Markers placed on the dorsal aspect of the rib cage and abdomen also moved during inspiration. Although motion in the cranial and lateral directions was small in magnitude and was not present in all subjects, motion in the ventral direction was substantial and was invariably present. This motion, which has not been reported previously, is not easy to explain. We do not think that it may be artifactual in nature and represent a skin motion artifact because sliding of markers around the elliptical perimeter of the rib cage and abdomen would be expected to produce a predominant displacement in the lateral, rather than in the ventral, direction. Similarly, involuntary flexion of the spine may be discarded because markers placed on the spine did not move (APPENDIX).

Alternatively, we suggest that the ventral displacement of the dorsal aspect of the chest wall observed here might be related to a ventral displacement of the center of gravity of the body during inspiration. Because the ventral aspect of the rib cage and of the abdomen moves outward during inspiration, the center of gravity of both compartments is expected to be displaced ventrally. If unopposed by contraction of paraspinal muscles, this alteration should result, in turn, in a ventral displacement of the trunk. Because in the present experiments the position of the spine was fixed, only the dorsal aspects of the rib cage and abdomen located laterally to the spine were allowed to move ventrally.

In summary, we have shown that, in normal subjects breathing at rest in the seated posture, displacements of the rib cage during inspiration are in the cranial, lateral, and ventral directions but that expansion of the abdomen is confined to the ventral direction. We have also demonstrated that the dorsal aspects of the two compartments move ventrally during inspiration.

APPENDIX

We made a specific experiment to verify the motionlessness of the spine in two subjects (*MP* and *VA*). We used an excavated support that allowed us to place four markers directly on the spine; one marker was fixed to the support, and 10 additional markers were attached to the rib cage and abdomen (Fig. 7*A*). Recordings of 30-s duration were performed on three occasions in the two subjects and showed that displacements of the markers fixed on the spine and on the support were of the order of magnitude of the noise (Fig. 7*B*). On the other hand, markers fixed to the dorsal aspect of the chest wall showed a significant ventral motion during inspiration (Fig. 7*B*).

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Address for reprint requests: M. Paiva, Biomedical Physics Laboratory, cp 613, Route de Lennik, 808, 1070 Brussels, Belgium.

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REFERENCES

1. **Agostoni, E.** Kinematics. In: *The Respiratory Muscles: Mechanics and Neural Control,* edited by E. J. M. Campbell, E. Agostoni, and J. Newsom Davis. London: Saunders, 1970, p. 23–47.
2. **Agostoni, E., P. Mognoni, G. Torri, and F. Saracino.** Relation between changes of rib cage circumference and lung volume. *J. Appl. Physiol.* 20: 1179–1186, 1965.
3. **D'Amico, M., and G. Ferrigno.** Technique for the evaluation of derivatives from noisy biomechanical displacement data using a model-based bandwidth-selection procedure. *Med. Biol. Eng. Comput.* 28: 407–415, 1990.
4. **D'Amico, M., and G. Ferrigno.** Comparison between the more recent techniques for smoothing and derivative assessment in biomechanics. *Med. Biol. Eng. Comput.* 30: 193–204, 1992.
5. **Ferrigno, G., P. Carnevali, A. Aliverti, F. Molteni, G. Beulcke, and A. Pedotti.** Three-dimensional optical analysis of chest wall motion. *J. Appl. Physiol.* 77: 1224–1231, 1994.
6. **Ferrigno, G., and A. Pedotti.** ELITE: a digital dedicated hardware system for movement analysis via real-time TV signal processing. *IEEE Trans. Biomed. Eng.* 32: 943–950, 1985.
7. **Jordanoglou, J.** Rib motion in health and disease. In: *The Thorax. Part B: Applied Physiology* (2nd ed.), edited by C. Roussos. New York: Dekker, 1995, vol. 85, p. 1071–1098. (Lung Biol. Health Dis. Ser.)
8. **Konno, K., and J. Mead.** Measurement of the separate volume changes of rib cage and abdomen during breathing. *J. Appl. Physiol.* 22: 407–422, 1967.
9. **Mead, J., N. Peterson, and G. Grimby.** Pulmonary ventilation measured from body surface movements. *Science* 156: 1383–1384, 1967.

10. **Milledge, J. S., and F. D. Stott.** Inductive plethysmography—a new respiratory transducer. *J. Physiol. (Lond.)* 267: 4P–5P, 1977.
11. **Saumarez, R. C.** An analysis of possible movements of human upper rib cage. *J. Appl. Physiol.* 60: 678–689, 1986.
12. **Smith, J. C., and S. H. Loring.** Passive mechanical properties of the chest wall. In: *Handbook of Physiology. Respiration. Mechanics of Breathing.* Bethesda, MD: Am. Physiol. Soc., 1986, sect. 3, vol. III, pt. 2, chapt. 25, p. 429–442.
13. **Vellody, V. P., M. Nassery, W. S. Druz, and J. T. Sharp.** Effects of body position change on thoracoabdominal motion. *J. Appl. Physiol.* 45: 581–589, 1978.
14. **Wade, O. L.** Movements of the thoracic cage and diaphragm in respiration. *J. Physiol. (Lond.)* 124: 193–212, 1954.
15. **Ward, M. E., J. W. Ward, and P. T. Macklem.** Analysis of human chest wall motion using a two-compartment rib cage model. *J. Appl. Physiol.* 72: 1338–1347, 1992.