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Research article

Coordination between ribs motion and thoracoabdominal volumes in swimmers during respiratory maneuvers

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Abstract

This work aimed to verify if swimmers present better chest wall coordination during breathing than healthy non-athletes analyzing the correlation between ribs motion and the variation of thoracoabdominal volumes. The results of two up-to-date methods based on videogrammetry were correlated in this study. The first one measured the volumes of 4 separate compartments of the chest wall (superior thorax, inferior thorax, superior abdomen and inferior abdomen) as a function of time. The second calculated the rotation angle of the 2nd to the 10th ribs around the quasi-transversal axis also in function of time. The chest wall was represented by 53 markers, attached to the ribs, vertebrae, thorax and abdomen of 15 male swimmers and of 15 non-athletes. A kinematical analysis system equipped with 6 digital video cameras (60Hz) was used to obtain the 3D coordinates of the markers. Correlating the curves of ribs rotation angles with the curves of the separate volumes, swimmers presented higher values than non-athletes when the superior and inferior abdomen were considered and the highest correlation values were found in swimmers for the inferior thorax. These results suggest a better coordination between ribs motion and thoracoabdominal volumes in swimmers, indicating the prevalent and coordinated action of the diaphragm and abdominal muscles to inflate and deflate the chest wall. The results further suggest that swimming practice leads to the formation of an optimized breathing pattern and can partially explain the higher lung volumes found in these athletes reported in literature.

Key words: Kinematics, thoracic wall volumes, ribs motion, swimming.

Introduction

It is already known that swimming training can modify the pulmonary function leading to higher pulmonary volumes and capacities than the predicted values or than the values achieved by athletes of other sport activities (Courteix et al., 1997). When pulmonary function was measured by traditional methods, like spirometry and body plethysmography, swimmers presented higher forced expiratory volume in one second (FEV1.0) as well as larger vital capacity (VC), total lung capacity (TLC), inspiratory capacity (IC), and functional residual capacity (FRC) (Armour et al., 1993; Clanton et al., 1987; Cordain et al., 1990; Courteix et al., 1997; Doherty and Dimitriou, 1997). However, the reasons for these alterations still remain unclear and although there are some hypothesis, like the increment in inspiratory muscle strength, alveolar distensibility, alveolar number, size of the lungs and chest wall or hereditary factors (Armour et al., 1993), there is not a consensus in the literature.

Chest wall motion is functionally related to ventilation. During inhaling, the inspiratory muscles contract, expanding the rib cage and further increasing its volume. This increase of volume lowers the air pressure in the alveoli to below atmospheric pressure, making the air rush in through the lungs. Although several physiological mechanisms involved with swimming practice have already been investigated, it is unknown if the chest wall coordination during breathing is also altered.Some studies have already identified alteration in both lung volumes and breathing patterns resulting from exercise and sport activities. Eastwood et al. (2001) concluded that the increase of inspiratory muscles performance found in marathon runners was a consequence of a difference in the breathing pattern adopted. Yoga exercises improve respiratory breathing capacity by increasing chest wall expansion and forced expiratory lung volumes (Chanavirut et al., 2006) and, besides the alteration in lung volumes, yoga techniques may also lead to the formation of optimized breathing patterns with an increased abdominal motion (Barros et al., 2003) Considering that swimming involves strenuous breathing efforts and since the higher lung capacities have already been demonstrated in swimmers, the coordination between the variation of the thoracoabdominal volumes and ribs motion could also be altered and the evaluation of these variables could be helpful to better understand the breathing mechanics and their alterations caused by intensive swimming practice. Such a modification could partially explain the alterations involving the respiratory system observed in swimmers, since the pattern of rib cage motion is strictly linked to the expansion and ventilation of the lungs.

Since rib cage and abdominal motion reflects, respectively, inspiratory rib cage muscles and diaphragm actions (Aliverti et al., 2003; Gilbert et al., 1981), thoracoabdominal pattern of breathing has been used as an index of ventilatory muscle function (Gallego et al., 1997) and alterations of thoracoabdominal volumes during exercise have been investigated (Kenyon et al., 1997; Sanna et al., 1999; Vogiatzis et al., 2005). The 3D coordinates of surface markers positioned on the chest wall, obtained by optoelectronic plethysmography, were used to calculate volumes of lung- and diaphragm apposed rib cage compartments and the abdomen during quiet breathing and exercise at 0, 30 50 and 70% maximum workload (Aliverti et al., 1997). A significant decrease was found in

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end-expiratory abdominal volume with an increasing end-inspiratory rib cage volume during exercise, reflecting the higher pressures generated by the inspiratory rib cage muscles during inhaling and the recruitment of abdominal muscles during exhaling, even at the lowest level of exercise.

Based on these assumptions, this work aims to verify if swimmers present better chest wall coordination during breathing than healthy non-athletes, through the analysis of the correlation between ribs motion and the variation of the thoracoabdominal volumes, obtained from kinematical analysis.

Methods

Data Collection

A group of 15 male swimmers (SG) was compared to a control group of 15 healthy non-athletes (CG). The criteria for inclusion in the SG were the following: a) participation in training activities for swimming competitions for more than 3 years, with this training occurring at least three times a week or covering an average of over 30.000 meters/month; b) effective participation in regional or national competitions. The mean age, weight and height of the swimmers were 20.7 (±2.4) years, 72.9 (±5.9) kg and 1.78 (±0.06) m, respectively. The CG was composed of male volunteers with no cardiopulmonary or postural diseases; they were non-swimmers, although they did exercise regularly. The mean age, weight and height of the non-athletes were 22.1 (±2.4) years, 72.3 (±10.5) kg and 1.78 (±0.06) m, respectively. The university ethics committee approved the research study (181/2003) and informed consent was obtained from all participants. Fifty anatomical retro-reflective markers (ϕ=5mm) were attached to the trunk of the subjects (Figure 1) and the three-dimensional coordinates of the markers were obtained with the kinematical analysis system *Dvideo* (Figueroa et al., 2003), with 6 digital video cameras (JVC-GR 9500) sampled at 60Hz. Synchronization of the camera registers was made using the audio band (Barros et al., 2006) while camera calibration and 3D coordinate reconstruction were based on the direct linear transformation method (Abdel-Aziz and Karara, 1971). The participants remained seated on a chair without back support, in a position involving abduction of the shoulders, knee flexion and feet on the ground. They were asked to avoid any movement unrelated to breathing during the performance of vital capacity maneuvers (VC): each subject performed 5 cycles of vital capacity breathing, defined as maximal inhaling followed by maximal exhaling.

From the 3D coordinates of the markers, the separate volumes of the chest wall and the ribs rotation angles were calculated as follow. The chest wall was divided in 4 compartments: superior thorax (ST – reflecting the action of neck and parasternal muscles); inferior thorax (IT – reflecting the action of parasternal muscles and diaphragm); superior abdomen (SA – reflecting the action of diaphragm and abdominal muscles); and inferior abdomen (IA – reflecting the action of abdominal muscles) (Figure 1-A). The coordinates of the 12 markers enclosing each compartment defined two irregular dodecahedrons, with 8 vertices each, that could be further divided into 6 tetrahedrons. The volume of each tetrahedron was computed by simple geometric formulas; the sum of these volumes gave the compartment volume while the sum of the volumes of all compartments defined the total volume of the trunk (Tk) (Loula et al., 2004).

After the volumes calculation, the angle of rotation of each pair of rib was calculated: a rib coordinate system was obtained for each pair of ribs (2^{nd} to 10^{th} rib) using the 3D coordinates of the markers positioned at the lateral extremity of the right and left ribs and at the spinous process of the corresponding thoracic vertebra (Figure 1-B), and a trunk coordinate system was calculated using the markers at the posterior superior iliac spines and the first thoracic vertebra. The rotation angle was then calculated around the quasi-transversal axis between the coordinate system associated to each pair of ribs and the coordinate system associated to the trunk, representing the upward and downward motion of the rib (Sarro et al., 2005).

The correlation coefficient was used to assess the relation between the two variables, measuring the strength of association between the curves of the rotation angles of the ribs and the curves of the separate thoracoabdominal volumes: the angle of each rib was correlated with the volume of each compartment and with the total volume of the trunk. High positive correlation values indicate that the compartment and the rib considered move in phase agreement, meaning the simultaneous increasing of the angle of rotation of the ribs and the compartment volume

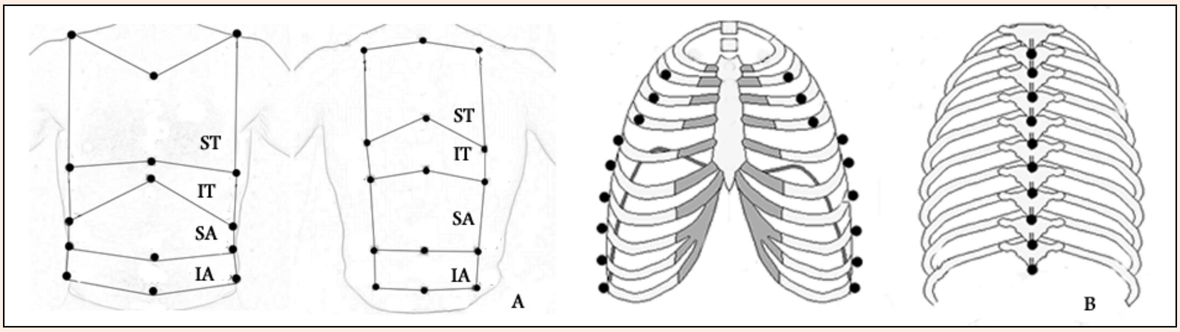

Figure 1. Representation of the trunk using external markers: model used to calculate the separate trunk volumes (A) and markers used to calculate the coordinate systems of the ribs (B). ST = superior thorax, IT = inferior thorax, SA = superior abdomen, IA = inferior abdomen;

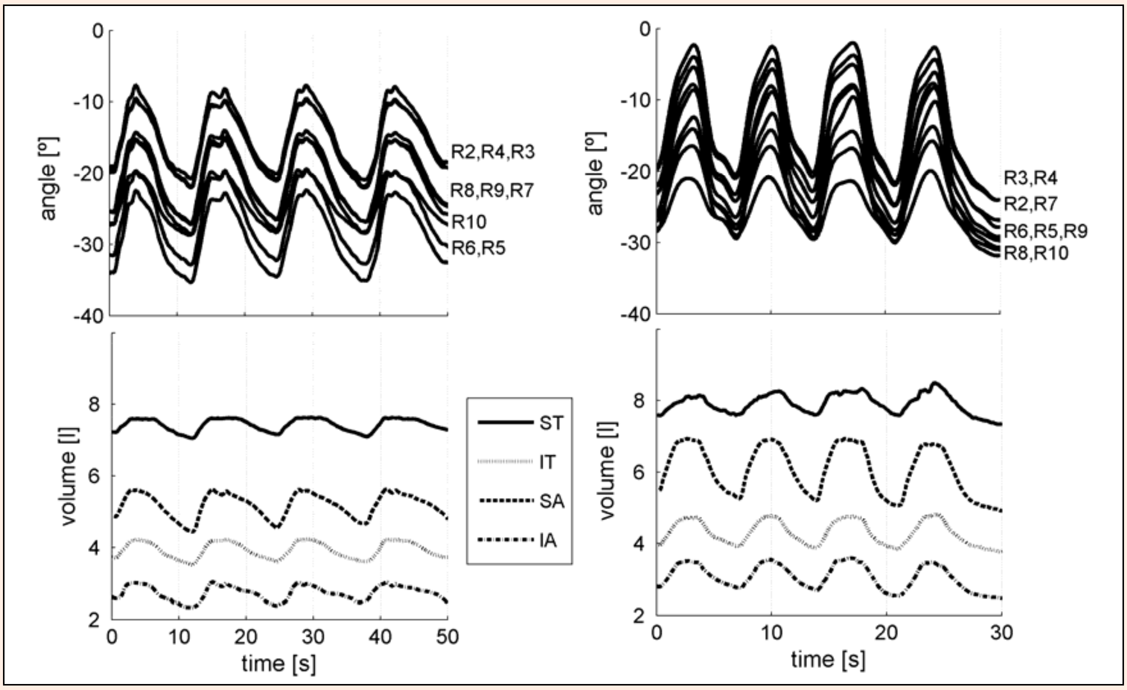

Figure 2. Rotation of the ribs (R2 to the R10) around the quasi-transversal axis and the 4 separate volumes of the chest wall of the subject of the control group (left) and the swimmer (right) that presented the highest correlation values. ST = superior thorax, IT = inferior thorax, SA = superior abdomen, IA = inferior abdomen.

at each instant and, hence, an efficient behavior to achieve maximum volumes (coordinated pattern). High negative correlation values reveal that the compartment and the rib considered move in opposite phase, meaning that whenever the increasing (or decreasing) of the angle of rotation of the ribs, there is a decreasing (or increasing) of the compartment volume at each instant and, so, an inefficient behavior of the ribs to increase volume (uncoordinated pattern). Values close to zero reveal that the compartment and the rib considered present an uncorrelated variation, varying separately at each instant.

Data analysis

The 3D coordinates were smoothed with a zero-phase forward and reverse Butterworth digital filter of 5th order (cutoff 1 Hz, revealed by spectral analysis). Considering that the correlation coefficient do not present a normal distribution, to the statistical analysis the Fisher z-transformation was applied (z-correlation coefficient) (Brownlee, 1960). The z-correlation coefficients between the rib rotation angles and the volume of chest wall compartments were obtained for each subject. Mean values were calculated over the subjects for the z-correlation coefficient between each rib and each compartment. The distribution of the mean values of the z-correlation coefficient obtained for each compartment was compared between the groups using a Box-plot representation (McGill et al., 1978). Each box indicates the lower quartile, median and upper quartile values, with dotted lines extending from each end of the box to show the extent of the rest of the data. The crosses represent the outliers, which are values higher or lower than 1.5 times the interquartile distance. The box also shows notches representing a robust estimate of uncertainties in relation to the medians for box-to-box comparison. Boxes with non-overlapping notches indicate that the medians of the two groups differ at the 5% level of significance. Since correlation coefficient is not additive, the mean correlation values presented in the results were calculated from the z-correlation coefficient and transformed back to correlation coefficient.

Results

The swimmer and the subject of the control group that presented the highest correlation values were selected to exemplify the analysis. Figure 2 shows an example of the ribs rotation angles around their quasi-transversal axes and the compartment volumes of the chest wall as a function of time presented by the control subject (left) and the swimmer (right) during vital capacity maneuvers. All these curves were obtained simultaneously from the 3D coordinate of the markers. It can be identified the correspondence between the ascending portion of the curves of the angles and the volumes with the inspiration phase of the breathing cycle as well as the correspondence between the descending portion of the curves of the angles and the volumes with the expiration phase of the breathing cycle. It is also remarkable the coordination among the ribs motion and the volume variation of the different chest wall compartments.

Table 1 shows the average of mean and standard deviation values of the rib rotation angles and of the volumes of the chest wall compartments presented by the control and swimmer group.

Correlating the ribs rotation angles and the volumes of the chest wall compartments high correlation values were found in both groups. Figure 3 shows the

Table 1. **Average of mean values and standard deviation values (std) of the ribs rotation angles and of the volumes of the superior thorax (ST), inferior thorax (IT), superior abdomen (SA), inferior abdomen (IA) and total trunk (Tk) presented by the control group (CG) and swimmer group (SG).**

		rib2	rib3	rib4	rib5	rib6	rib7	rib8	rib9	rib10	ST	IT	SA	IA	Tk
CG	mean	-21.5	-22.6	-24.4	-36.7	-30.9	-25.8	-24.4	-23.9	-24.8	7.0	3.4	5.7	2.5	18.8
	SD	5.6	5.1	4.67	4.4	4.5	4.6	4.2	3.5	2.6	0.3	0.2	0.4	0.1	1.0
SG	mean	-12.7	-10.6	-10.0	-20.8	-18.7	-17.7	-17.4	-19.6	-22.7	7.2	3.8	5.0	3.0	19.0
	SD	7.2	6.7	6.0	6.4	6.3	5.8	5.3	4.5	3.6	0.8	0.6	0.8	0.7	2.2

distribution of the mean values of the z-correlation coefficients between the volumes of the chest wall compartments and the ribs rotation angles presented by the control group and the swimmer group in a box plot representation. Comparing the results between the groups, the control group presented statistically significant higher values ($p < 0.05$) correlating the volume of ST with ribs angles (mean correlation coefficient of 0.95), while the swimmer group presented statistically significant higher values for the SA (mean correlation coefficient of 0.96) and IA (mean correlation coefficient of 0.92). The highest statistically significant difference between medians was found in the inferior abdomen, where the control group presented the smallest correlation values (mean correlation coefficient of 0.77). Although no statistically significant differences were found for IT the highest values were found in the swimmer group for this compartment (mean correlation coefficient of 0.97).

Discussion

The aim of this experiment was to verify the chest wall coordination of swimmers during breathing from the correlation of the results of two up-to-date methods based on videogrammetry. Using the 3D coordinates of markers positioned on the trunk surface, obtained by kinematical analysis, the rotation angles of the ribs (2 to 10) and the volume of four chest wall compartments were calculated as a function of time. All the rotation angles as much as the volumes of the four compartments presented a signal coherent with breathing cycle and high correlation was found between them, for both control and swimmer groups.

Comparing the groups, the control group presented higher values when the superior thorax was considered, showing that ribs motion is more associated with the volume variation of the superior thorax. Swimmer group presented higher correlation between ribs rotation angles and variation of the volume of superior and inferior abdomen, pointing a better association of ribs motion with these compartments. Although no statistical difference was found between the groups considering inferior thorax, the highest correlation values were found for this compartment in the swimmer group. Since during inspiration the diaphragm is responsible for the displacement of the abdomen and the inferior thorax (which represents the region of apposition between the diaphragm and the rib cage) (Ward et al., 1992), these results could be explained by the prevalent action of the diaphragm of the swimmers during vital capacity maneuvers. Furthermore, the abdominal muscles also play an important role: they deflate the inferior thorax during expiration and allow the abdominal pressure to decrease throughout inspiration, in parallel with pleural pressure, allowing the diaphragm to contract (Aliverti et al., 1997). Based on this assumption, the high correlation found in swimmers between rib motion and abdominal volumes could be attributed to a better coordinated action of both inspiratory and expiratory muscles during vital capacity maneuvers.

According to Masliah (1999), a coordinated

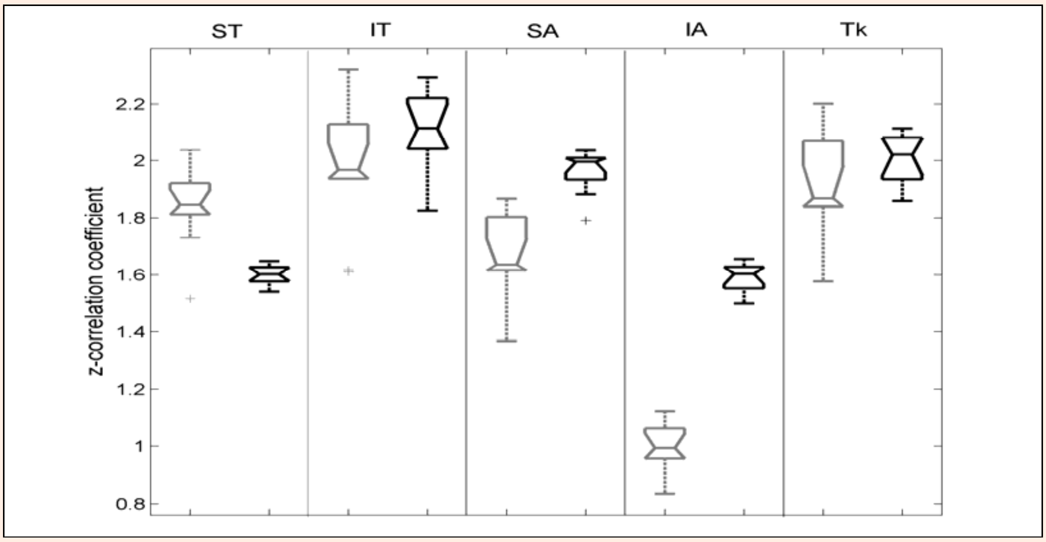

Figure 3. **Distribution of the mean values of the z-correlation coefficient between the ribs angles and the volumes of each compartment of the chest wall presented by the control group (grey) and swimmer group (black) during vital capacity maneuvers.** ST = superior thorax, IT = inferior thorax, SA = superior abdomen, IA = inferior abdomen, Tk = total trunk.

movement is generally recognized as being an efficient movement. Hence, the results showed the improved efficiency of the diaphragm and abdominal muscles of swimmers to displace coordinately the rib cage and abdomen when the respiratory system is submitted to higher efforts like maximal breathings, the most used by the swimmers during training. This optimization of the breathing pattern found in swimmers reinforces the idea that practicing swimming can promote positive changes in the thoracoabdominal motion.

Breathing pattern optimization was found by Barros et al. (2003) in yoga practitioners, correlating the variation of the thoracic and abdominal areas during VC maneuvers. They found that yoga practice induced a pattern in phase agreement in the variation of thoracic area and abdominal area during vital capacity maneuvers.

Aliverti et al. (1997) affirm that the central drive to the various respiratory muscle groups changes during exercise according to exercise workload and is translating into velocity of shortening or force depending on the load against which the muscles act. Although the load imposed to the respiratory muscles by water resistance and by the thorax compression caused by excessive contraction of upper limbs and back muscles, swimmers do not present higher respiratory muscle force when compared to non-athletes or athletes of other modalities (Cordain et al., 1990; Armour et al., 1993). So, the intense requirement of the respiratory system during regular swimming training might change the central drive to the respiratory muscles, leading to a better coordination of the chest wall.

The major contribution of this work was the identification of this optimized breathing pattern in swimmers, not yet reported in the literature. One of the limitations of the study is the fact that correlation does not suggest a cause-effect relationship but only the degree of concomitance between the variables and, so the cause of which may be unknown. Nevertheless, the significance of the finding cited above remains in the fact that this optimized pattern can be necessary to the increment of breathing performance and can also partially explain the higher lung volumes of swimmers reported in literature, calling for new investigations involving breathing patterns and lung volumes.

Conclusion

The results of this study showed that there is a high correlation between the ribs motion and the variation of thoracoabdominal volumes. This correlation is higher in swimmers than non-swimmers considering the abdominal region, which is under the coordinated action of diaphragm and abdominal muscles. This result suggests that swimming practice might lead to the formation of an optimized breathing pattern, increasing the coordination between the thoracoabdominal volumes and the ribs motion.

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Key points

- The study revealed that swimmers present higher correlation between the ribs motion and the variation of abdominal volumes than non-swimmers, suggesting that swimming practice might lead to the formation of an optimized breathing pattern, increasing the coordination between the thoracoabdominal volumes and the ribs motion.
- No previous work was found in the literature reporting this optimized breathing pattern in swimmers.
- The higher coordination between the thoracoabdominal volumes and the ribs motion found in swimmers can partially explain the higher lung volumes reported in literature for these athletes.

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