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Comparison of marker models for the analysis of the volume variation and thoracoabdominal motion pattern in untrained and trained participants

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Abstract

Respiratory assessment and the biomechanical analysis of chest and abdomen motion during breathing can be carried out using motion capture systems. An advantage of this methodology is that it allows analysis of compartmental breathing volumes, thoraco-abdominal patterns, percentage contribution of each compartment and the coordination between compartments. In the literature, mainly, two marker models are reported, a full marker model of 89 markers placed on the trunk and a reduced marker model with 32 markers. However, in practice, positioning and post-process a large number of markers on the trunk can be time-consuming. In this study, the full marker model was compared against the one that uses a reduced number of markers, in order to evaluate *i)* their capability to obtain respiratory parameters (breath-by-breath tidal volumes) and thoracoabdominal motion pattern (compartmental percentage contributions, and coordination between compartments) during quiet breathing, and *ii)* their response in different groups such as trained and untrained, male and female.

Although tests revealed strong correlations of the tidal volume values in all the groups (R^2>0.93), the reduced model underestimated the trunk volume compared with the 89 marker model. The highest underestimation was found in trained males (bias of 0.43 L). The three-way ANOVA test showed that the model did not influence the evaluation of compartmental contributions and the 32 marker model was adequate to distinguish thoracoabdominal breathing pattern in the studied groups.

Our findings showed that the reduced marker model could be used to analyse the thoracoabdominal motion in both trained and untrained populations but performs poorly in estimating tidal volume.

Keywords: thoracoabdominal motion, breathing, respiratory assessment, volume, coordination.

Word Count: 1978 words

Introduction

By tracking the three-dimensional coordinates of a number of photo-reflective markers positioned on the trunk of the subject, motion capture systems (A Aliverti et al., 2001; Massaroni et al., 2017a), are capable of tracking chest wall motion and so can *i)* measure respiratory volumes *ii)* assess thoracoabdominal motion and *iii)* evaluate coordination among chest wall compartments.

Breathing assessment models described in previous studies (Ferrigno et al., 1994; Massaroni et al., 2017a) suggest the following factors are important: *i)* sufficient landmarks to estimate the chest surface; *ii)* location of markers to minimise soft tissue motion; *iii)* repeatability of marker postioning. Four models allowing breathing assessment have been described and applied on healthy and pathological subjects in the standing position, based on 89 (Aliverti et al. 2001), 86 (Cala et al., 1996), 32 (Ferrigno et al., 1994) and 30 markers (Loula et al., 2004). The 89 marker model would seem to allow a more accurate reconstruction of the chest wall surface and is therefore considered the gold standard. However, the high number of markers required can affect reproducibility of measurements, and the time to place makers, the collection and post-processing of data from 89 markers in proximity can be challenging and time-consuming. This reduces the utility of such a system to provide rapid and timely diagnosis or treatment and training for clinical and athletic populations. However, differences between the application of these models and their outcomes regarding respiratory assessment have not yet been analyzed in the literature. Hence, they have been considered equivalent despite the absence of experimental evidence.

The aim here was to compare the most widely used reduced marker model (based on 32 markers) with the gold standard model of 89 markers in order to compare the breath-by-breath tidal volumes, and the thoracoabdominal motion pattern (compartmental percentage contributions, and coordination between compartments) obtained using each model during quiet breathing. Additionally, differences between trained and untrained sub-groups were evaluated.

Methods

Experimental Setup:

Marker models: In the 89 marker model, markers are placed on the chest wall surface along seven horizontal rows between the clavicles and the anterior superior iliac crest with additional bilateral columns in the mid-axillary line to create the anterior view (BTS Bioengineering, 2011). The rib cage is subdivided into two main compartments: RCp and RCa. RCp extends from the clavicles to the line of markers spreading transversely at the level of the xiphisternum, whereas RCa extends from this line to the lower costal margin. AB covers the caudal parts of the frontal trunk, from the lower costal margin to the level of the anterior superior iliac crest. Seven posterior horizontal rows (between C7 and the posterior axillary lines) contribute to the coverage of the back. (BTS Bioengineering, 2011; Layton et al., 2011; Parreira et al., 2012).

The 32 marker model is a subset of the 89 marker model: the anterior frame consists of four horizontal rows (2nd rib, xiphoid process, 10th rib, and abdominal transversal line) and four equally spaced vertical rows starting from between the anterior and midaxillary lines, with a symmetric posterior grid.

Both models allow the computation of *i)* the contribution of the upper and lower thorax and abdomen to the breathing kinematics, and *ii)* the contribution of the left, center, and right side of the trunk to the respiratory motion. (Ferrigno et al., 1994). In this context, the upper thorax compartment reflects the action of the neck and parasternal muscles, and the effect of pleural pressure; the lower thorax compartment represents the work of the diaphragm and the effect of abdominal and pleural pressure; and the abdomen compartment reflects diaphragmatic motion and the work of abdominal muscles.

Study participants: Experimental trials were undertaken in two EU laboratories, and compared the breathing volumes in two populations, i.e., ten untrained healthy volunteers (UT, five males and five females, Italy) and ten male trained healthy volunteers (TR, United Kingdom). Characteristics of the study participants are reported in Table I.

Table I: Participants characteristics: age, weight, height and number of breaths collected in one minute during the trials. The average (Avg) and the standard deviation (SD) values are also reported per each group.

Group	Volunteer	Age	Weight	Height	Breaths/min
UT males	1	22	58	172	10.9
	2	22	70	180	14.0
	3	27	60	168	10.8
	4	22	72	174	8.1
	5	25	71	178	21.5
	Avg ± SD	24±2	66±7	174±5	13.1±5.2
UT females	1	23	57	163	18.0
	2	26	52	158	15.1
	3	22	57	169	19.2
	4	21	59	173	28.4
	5	21	53	164	21.4
	Avg ± SD	23±2	56±3	165±6	20.4±5.0
TR males	1	28	73	172	18.7
	2	34	69	188	14.3
	3	37	67	182	16.1
	4	34	82	174	12.1
	5	38	77	171	11.6
	6	32	70	182	16.0
	7	38	66	177	11.4
	8	35	63	168	19.6
	9	22	65	183	9.6
	10	21	70	176	9.7
	Avg ± SD	32±6	70±6	177±6	13.9±3.6

The Italian laboratory used an 8-camera motion capture system (D-Smart, BTS Bioengineering Corp., Italy, sampling rate of 60 Hz), positioned in a 360° circular pattern to cover 360°, approximately 3 meters from the subject. Each UT volunteer was instructed to breathe quietly in a standing position. In the UK laboratory, a 10-camera motion capture system (Qualisys AB, Sweden) was set up in the same configuration. Each TR volunteer was seated on an upright cycle ergometer (Lode Corival, Groningen, Netherlands). To minimise upper body motion and avoid interference with data acquisition, arms were positioned on supports at 90° to the trunk in the scapular plane. Trunk movements were recorded for 30 s.

The University of Kent, School of Sport and Exercise Sciences' Local Research Ethics Committee, Chatham Maritime, UK (Reference Number: Prop17_2013_14) approved the study. The principles of the Declaration of Helsinki were followed in all steps of the study, and each participant gave written informed consent to take part in the study.

<u>Breathing volume computation:</u> A previously reported geometric model (Massaroni et al., 2017b) was implemented using custom MATLAB code to compute the chest volume from the 3D marker coordinates. Details in Appendix A.

<u>Data Analysis:</u> From the 3D markers coordinates, compartmental and total chest volumes were computed using the 89 marker and 32 marker models.

Trunk tidal volume analysis: During quiet breathing, the trunk tidal volume (TV_{total}) (the difference between end-inspiratory and end-expiratory volume) was calculated for each breath. Bespoke MATLAB code identified the minimum signal peaks identify each breath and to compute the TV_{total}. All TV_{total} values obtained from the 89-marker model were compared against the corresponding 32 marker TV_{total} values per each group (UT and TR male, UT female) and a Bland-Altman analysis was carried out to evaluate the mean of difference (MOD) between the volume variations obtained by using the two measurement methods, as well as the limits of agreement (LOA) calculated as the mean difference ±1.96 the standard deviation (SD)..

Thoracoabdominal motion pattern analysis:

To compare the thoracoabdominal pattern between marker models, we used the percentage contribution of each compartment to the total volume and the coordination between compartments.

Compartmental contributions:

From the TVs calculated from the compartmental volumes (i.e., RCp, RCa, AB) the percentage contribution of each compartment to the total volume for each i-th breath ($\%RCp^{i}, \%RCa^{i}, \%AB^{i}$) was calculated, and then averaged for all breaths for both the 89 and 32 marker models for each volunteer ($\%\overline{RCp}, \%\overline{RCa}, \%\overline{AB}$).

The differences between the averaged percent contribution of each compartment using the 32-marker model and the 89 marker model were then calculated ($\Delta\%RCp, \Delta\%RCa, \Delta\%AB$).

The $\sin^{-1}$ transformation was applied to the percentage contribution of each compartment on the total volume to approximate a normal distribution (Zar and H., 2010).

Coordination between compartments:

Pearson's squared coefficient (R^2) analysed the coordination between each pair of curves as function of time of the compartments RCp, RCa, AB (i.e, RCp *vs* RCa, RCp *vs* AB, RCa vs AB and RC (obtained as the sum of RCp and RCa) *vs* AB (Silvatti et al., 2012).

Fisher's z-transformation (Zar and H., 2010) was applied to the original correlation coefficients as in (1):

$$z = \frac{\ln(1+r)}{2 \cdot (1-r)} \qquad (1)$$

where *ln* is the natural logarithm and *r* is the correlation coefficient value. Three-way ANOVAs with three factors and all interactions were used to compare percentage compartment contributions and the z score: (a) group, with three levels (UT males, UT females and TR); (b) marker model, with two levels (32 model and 89 model) and (c) compartment, with three levels (RCp, RCa and AB).

Results

Trunk tidal volume

TV_{total} values showed high correlation between the 89 marker and 32 marker models. In all three groups, R^2 was higher than 0.93 (Figure 1). The lowest R^2 value was found in the TR population, where the TV_{total} range was 3.5 L over 122 breaths. Comparable results were obtained in both the UT groups.

The Bland Altman analysis of the MOD value shows a significant underestimation when the 32-marker set is adopted for all groups. MOD values were considerably different between groups: even in the UT groups, we found an underestimation of 0.24 L ($p<0.001$) and 0.14 L ($p<0.001$), for males and females, respectively. The TR group showed a bias of 0.43 L ($p<0.001$). The

LOAs values demonstrated better precision of the reduced marker model for the female group (LOAs interval: females ±0.14 L, UT male group ±0.24 L, TR group ±0.43 L).

FIGURE 1

Thoracoabdominal motion pattern analysis:

Compartmental contributions:

Table II reports the differences between marker models (Δ%) for each volunteer. In the UT male group, the %RCp was always underestimated compared to the 89-marker model. In 18 out of 20 participants, the %RCa was overestimated, when the 32-marker model was used, while the %AB was generally overestimated in the UT groups, but not in the TR one.

Figure 2 shows the boxplot obtained using the values of percentages for each compartment for each group.

Table II: Compartmental percentage contributions: differences between marker models (Δ%) are reported for each subject.

		Δ%		
Group	**Volunteer**	**RCp**	**RCa**	**AB**
UT males	1	-2.32	2.16	0.22
	2	-5.85	4.24	1.60
	3	-3.80	2.45	1.29
	4	-0.26	-2.83	3.30
	5	-5.60	1.48	5.40
UT females	1	1.61	-0.07	-0.98
	2	0.23	0.54	1.78
	3	-3.59	1.40	2.29
	4	-1.49	0.82	1.09
	5	-4.48	2.75	2.08
TR males	1	2.38	7.48	-8.19
	2	-1.30	5.25	-3.51
	3	-0.68	3.74	-2.16
	4	1.00	2.39	-2.88
	5	-1.07	1.15	1.23
	6	-7.96	2.76	5.70
	7	-1.70	3.24	-0.33
	8	3.55	0.31	-2.30
	9	-8.17	4.88	3.34
	10	-2.26	5.88	-2.84

FIGURE 2

Percentage contributions did not change with training level (UT vs TR) (p=0.24). The marker model main factor (p=0.48) and all interactions were not significant (p=0.27-0.9), suggesting marker model does not influence the evaluation of percentage compartmental contributions. Conversely, significant differences were found for the main factor compartment (p<0.0001) and the group and compartment interaction (p<0.0001). A *post-hoc* Tukey test revealed that RCp contribution to the total volume was significantly higher than AB contribution, and both (RCp and AB) were significantly higher than RCa. This compartmental pattern was found in the UT males group, but the pattern was different for the TR group; RCp and AB were more involved in the motion than RCa**.**

Coordination between compartments:

The mean values of the correlation coefficients of each compartment combination for the three groups are shown in Table III, for each subject and both marker models.

The correlation coefficients were lower for TR individuals (UT males>UT females >TR, *p*<0.0001). The marker model main factor (*p*=0.26) and all interactions were not significant (*p*=0.63-0.85). This suggests marker model did not influence the evaluation of compartmental contributions.

Table III: Correlation coefficients (Pearson's squared coefficient) for each participant, obtained from both the marker models.

		RCp vs RCa		**RCa vs AB**		**RCp vs AB**		**RC vs AB**	
Group	**Volunteer**	**32 m**	**89 m**	**32 m**	**89 m**	**32 m**	**89 m**	**32 m**	**89 m**
UT males	1	0.97	0.96	0.99	0.99	0.97	0.95	0.99	0.97
	2	0.99	0.98	0.99	0.98	0.98	0.95	0.99	0.96
	3	0.98	0.97	0.98	0.97	0.96	0.92	0.97	0.95
	4	0.92	0.97	0.96	0.98	0.90	0.94	0.93	0.96
	5	0.99	0.98	0.96	0.98	0.97	0.96	0.97	0.97
UT females	1	0.97	0.97	0.91	0.89	0.90	0.89	0.91	0.90
	2	0.94	0.96	0.84	0.95	0.90	0.95	0.90	0.95
	3	0.97	0.94	0.94	0.93	0.94	0.91	0.95	0.93
	4	0.98	0.96	0.99	0.98	0.97	0.95	0.98	0.97
	5	0.98	0.97	0.97	0.94	0.97	0.92	0.97	0.93
TR males	1	0.90	0.88	0.85	0.86	0.81	0.88	0.84	0.90
	2	0.96	0.94	0.92	0.91	0.95	0.96	0.95	0.96
	3	0.96	0.95	0.96	0.95	0.92	0.95	0.95	0.96
	4	0.97	0.95	0.88	0.92	0.94	0.95	0.92	0.95
	5	0.91	0.87	0.73	0.80	0.78	0.82	0.78	0.84
	6	0.95	0.95	0.97	0.97	0.88	0.91	0.92	0.93
	7	0.93	0.89	0.89	0.89	0.94	0.92	0.94	0.94
	8	0.94	0.91	0.93	0.95	0.89	0.94	0.92	0.97
	9	0.96	0.96	0.80	0.73	0.83	0.79	0.83	0.78
	10	0.95	0.94	0.80	0.85	0.83	0.85	0.83	0.87

Discussion

In this study we compared the gold standard 89 marker model with the 32-marker model in terms of: *i)* tidal volume measurements; *ii)* compartmental contribution to the total tidal volume; *iii)* coordination between compartments.

TV_{total} from the two models correlated strongly for all groups (R^2 always > 0.93). Nevertheless the values in our study were slightly lower than those reported by Cala et al. (R^2=0.99) (Cala et al., 1996). However, the 32-marker model significantly underestimated TV_{total} when compared to the 89 marker model values. TR resulted in the highest MOD and LOAs values possibly due to different positioning of the participants in the two groups during data collection. Although the RCp was always overestimated in the 32-marker model, marker model did not influence the evaluation of compartmental contributions. This suggests the 32-marker model adequately distinguishes between thoracoabdominal breathing pattern in males and females. This finding is line with a previous report (Silvatti et al., 2012).

Moreover, correlation coefficient values – used to analyse the coordination of the chest wall compartments – demonstrated a maximum deviation of 0.13 between values. Additionally, no significant difference was found when the factor markers model and all the interactions with this factor was analysed. These findings suggest both models are valid for the identification and analysis of compartment coordination. It is important to highlight, that in contrast to the study of Silvatti et al. (Silvatti et al., 2012) that showed trained swimmers presented a more coordinated thoracoabdominal movement, our results revealed that the chest wall motion of the TR group was less coordinated than of the control groups (UT males and females). This may be because our trained participants undertook different sports, potentially leading to different breathing patterns.

The main limitation of this study in the experimental trials was the differing body positioning between the UT and TR participants, which may have influenced the results in the two groups. Further developments will be devoted to test participants at different intensities with the proposed marker model.

Our findings suggest a reduced model of 32 markers can be used to analyse the thoracoabdominal motion pattern in both trained and untrained populations, which may be more practical for the assessment of breathing volumes and mechanics, particularly in athletes and clinical populations.

Conflict of Interest Statement

None.

Acknowledgments

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APPENDIX A

The coordinates of the body landmarks were used as a starting point for the geometric model to compute volume. Each compartment consists of eight markers: four on the front and four on the back of the chest (some compartments share the same markers). The 8 markers identify 6 tetrahedrons (Massaroni et al., 2017b, 2017c). The volume of each tetrahedron is computed starting from the coordinates of its vertices. By considering a generic tetrahedron with vertices $P_1P_2P_3P_4$ the volume enclosed can be calculated as in (1):

$$V = \frac{1}{6}\left|\det(V_1, V_2, V_3)\right| = \frac{1}{6}\left|\det\begin{bmatrix} 1 & x_{P_1} & y_{P_1} & z_{P_1} \\ 1 & x_{P_2} & y_{P_2} & z_{P_2} \\ 1 & x_{P_3} & y_{P_3} & z_{P_3} \\ 1 & x_{P_4} & y_{P_4} & z_{P_4} \end{bmatrix}\right| \quad (1)$$

where $V_1=P_2-P_1$, $V_2 = P_3-P_2$ and $V_3 = P_4-P_3$.

The sum of all tetrahedral equals the total chest volume, and the sum of the tetrahedral volumes in each compartment adds up to the compartmental volume. The higher the number of compartments, the better the approximation of the enclosed volume is. The compartmental analysis is useful to assess the contribution of each single compartment of the trunk to the total respiratory motion. This aspect provides respiratory movement patterns which can highlight different conditions (e.g., healthy or pathological, trained or untrained individuals).

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Figure 1: Correlation and Bland-Altman analysis between TVs collected by trunk volume computed with the 89 markers model and TVs collected by the trunk volume (TV_{total}) computed with the 32 markers model on UT male and female and TR males. In the correlation plot the dashed line is the line of best fit; in the Bland-Altman the dashed lines are the LOAs while the continuous line is the MOD.

Figure 2: Boxplots report the compartmental percentages calculated with both the 89 and 32 marker models for the three groups (UT males and females and TR males) for the three compartments. The red line is the median of the distribution; the upper and lower quartile are shown in the blue box as well as the maximum and minimum value with black dashed lines. Outliers are reported as red crosses.