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Thoracic and abdominal breathing volumes in various body positions

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Abstract: Optoelectronic plethysmography, a non-invasive motion capture technique, calculates the tidal volume and tracks chest wall motions. This study used a motion capture system and a compression shirt with markers embedded in anatomical landmarks as optoelectronic plethysmograph to measure trunk movement in three different positions (standing, sitting, and lying). The recorded data were then processed to compare the contribution of thoracic and abdominal breathing during these three positions. The study showed that abdominal breathing predominates at low tidal volumes and when lying supine. The development of Smart-Shirts for breath analysis can be supported by the outcomes modeling approaches that could be improved.

Keywords**:** Optoelectronic plethysmography, Motion capture system, Tidal Volume, Abdominal breathing, Thoracic breathing.

1. INTRODUCTION

A life-threatening disease known as acute respiratory distress syndrome (ARDS) may be brought on by widespread lung inflammation or severe infections like the coronavirus COVID-19 (Hadaya et al., 2020). The widespread condition known as chronic obstructive pulmonary disease (COPD) is treatable and prevented. Progressive airflow restriction and hyperinflation, along with breathlessness or dyspnoea and changed breathing patterns, are its defining characteristics that worsen over time and are one of the significant causes of illness and mortality worldwide (Varga et al., 2015).

Changing the body position can improve the therapy and healing process for various diseases. Thus, patients with acute respiratory distress syndrome can breathe more accessible by being positioned prone (Hadaya et al., 2020). And also, despite sparse data, according to Mikelsons et al. (Mikelsons et al. 2008), changes in posture and breathing techniques are common physical therapy treatments used to relieve dyspnoea. Romei et al. (Romei et al., 2010) mention that the displacement of the rib cage was significantly impacted by posture.

1.1 Chest surface motions

Chest surface motion carries information about the respiratory and cardiac systems and the intricate interactions between these two systems (Shafiq et al., 2017). Various factors might affect respiration, including body posture (Hoit et al., 1995; Marrow et al., 2016). The posture (laying, sitting, or standing) effects the ribcage (chest wall) and the abdominal expansion and contraction. This expansion and contraction of the upper body directly provide information about the inhalation and exhalation of a subject. A correlation between respiratory-related upper-body surface motions and tidal volumes is unquestionably existent, and chest surface motion is critical for individual cardiorespiratory monitoring systems (Shafiq et al., 2017).

1.2 Optoelectronic Plethysmography (OEP)

Massaroni et al. (Massaroni et al., 2017) mentioned that a non-invasive motion capture technique called optoelectronic plethysmography (OEP) is used to record chest wall motions and calculate respiratory volumes. The history of motion capture can be traced back to Max Fleischer in 1915 when he developed the rotoscope technique for capturing human motion. The essential technological advance was made in 1990 by Pedotti (Cerveri et al., 2005), who employed a method to reduce the effect of skin artifacts on a motion capture system that uses a marker-based posture analysis. Further advancements happened when (Cala et al., 1996) were the first to employ a motion analysis-based system that theoretically allowed for the measurement and observation of the movement of several points via optical reflective markers.

According to Parreira et al. (Parreira et al., 2012), OEP enables the measurement of characteristics such as breathing pattern, breathing asynchrony, and tidal volume contributions from each compartment of the chest wall and the hemithorax. However, as Irisz et al. (Irisz et al., 2016) reported, the OEP has been demonstrated to be a technique for assessing respiratory parameters in healthy participants and subjects with various dysfunctions in various ways, positions, circumstances, and settings.

However, since the OEP is a complex and expensive measuring device, it is used predominantly in science and research (Laufer et al., 2023). In clinical applications, it is usually used to monitor the breathing of premature infants, whose breathing must not be influenced in any way by the measurement.

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1.3 State of the art

In clinical practice, spirometry and physical examinations are typically used to assess respiratory function. Spirometry is essential to pulmonary diagnostics, as spirometry can easily and quickly determine some important respiratory parameters (Hayes and Kraman, 2009; Miller et al., 2005). For more sophisticated measurements or when total lung capacity or airway resistances are of interest, body plethysmography (Coates et al., 1997; Criée et al., 2011) can be performed. Both spirometry and body plethysmography can quantify lung volume and airflow, and the results can be objectively compared with other measurement methods.

However, neither spirometry nor body plethysmography cannot distinguish between abdominal breathing and thoracic breathing. Both measurement techniques can be exhausting for the patients and cause uncomfortable situations due to breathing only from the mouth, and this inconvenience can even influence the measurement itself (Gilbert et al., 1972).

It has been attempted for some time to determine respiratory parameters via surface movements on the upper body in order to circumvent airflow measurement (spirometry and body plethysmography). There have been many different approaches (Laufer et al., 2020; Karacocuk, 2019) that have tried to determine respiratory volumes differently. To further this development, it is also interesting how the surface movements change in different body positions or how the proportion of abdominal to thoracic breathing shifts in different body positions.

This article uses the MoCap markers and the motion tracking system to study and analyze the breathing pattern of four healthy subjects in different body positions and study the effect of position on the thoracic to abdominal breathing.

2. PROCEDURES AND METHODOLOGY

2.1 Motion capture system and setup

Nine infrared motion tracking cameras (VICON Bonita B10, Firmware Version 404), as shown in Figure 1, were used for this investigation. The OEP motion capture technology was used with a body-fit T-shirt covered by motion capture markers. The markers' movement was captured using a camera-based motion capture system MoCap (Bonita, VICON, Denver, CO), which delivers the center point of each MoCap marker at each time. To obtain precise volume information, the MoCap marker positions were corrected afterward in such a way that the given positions represent the point under the MoCap marker directly on the skin surface of the subjects (see Laufer et al., 2020a).

As indicated in Figure 2 and Figure 3, a total of 102 MoCap markers were affixed to the T-shirt. The markers were arranged and organized to form 7 distinct levels. Each level, from level 4 to level 7, of the T-Shirt consisted of 16 markers. The first level had nine markers, second and third levels had 14 markers. In addition, a reference marker was attached to the T-shirt, which was located on the cervical spine between (C4 – C6). The rest of the markers were distributed in 7 levels, as shown in Table 1. These positions are only approximations and may differ slightly depending on the size of the participants. The reference marker (level 0) was included to allow later corrections of movements that are not respiration induced.

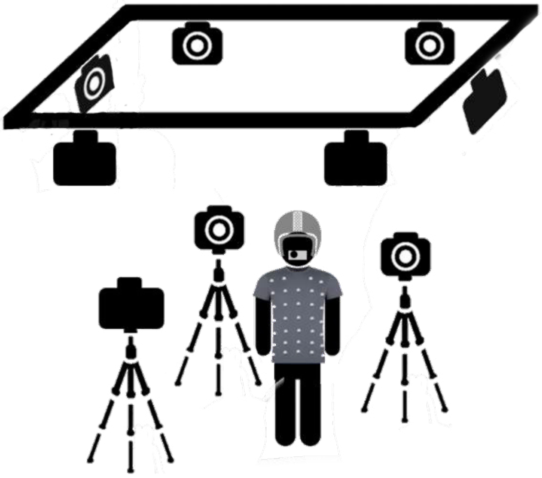

Fig 1. Motion capture setup and camera arrangement.

Table 1. Markers' position

Level	0	1	2	3	4	5	6	7
Position Ribcage	-	R1	R2 – R3	R4 – R6	R7 – R8	R9 – R12	-	-
Position Vertebrae	C4 – C6	C7 – T1	T3 – T5	T6 – T8	T9 – T11	T12 – L1	L2 – L3	L3 – L5

In accordance with the anatomy of the human upper body, levels 0 to 4 depicted the thoracic region of the body, and levels 4 to 7 covered the abdominal region (as shown in Figure 2). Therefore, this distribution was used to distinguish abdominal volume from thoracic volume.

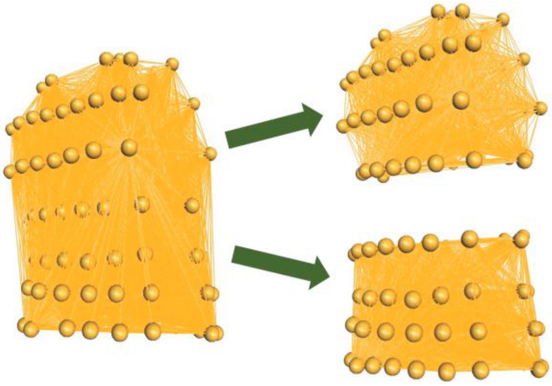

Fig 2. The obtained volume, based on the MoCap data, was split into abdominal volume and thoracic volume.

2.2 Study Subjects and Procedures

Four healthy participants took part in this study. The details of the participants are shown in Table 2.

Table 2. Subjects' information

Subject	Age	Height (cm)	Weight (Kg)	Gender
1	24	160	72	male
2	22	147	56	female
3	23	164	60	female
4	33	165	70	male

Each participant received instructions about the whole process. The measurements were taken while breathing in various body positions (standing, sitting, and lying supine), as shown in Figures 3 a, b, and c.

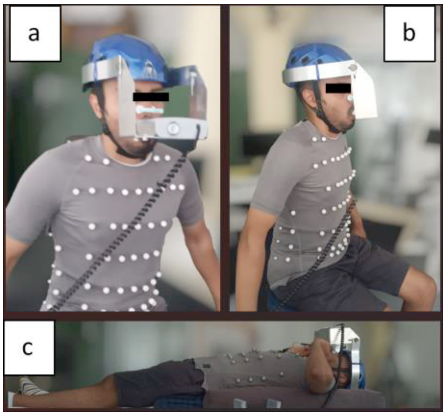

Fig. 3. Breathing postures applied in this study, (a) standing position, (b) sitting position, and (c) laying position.

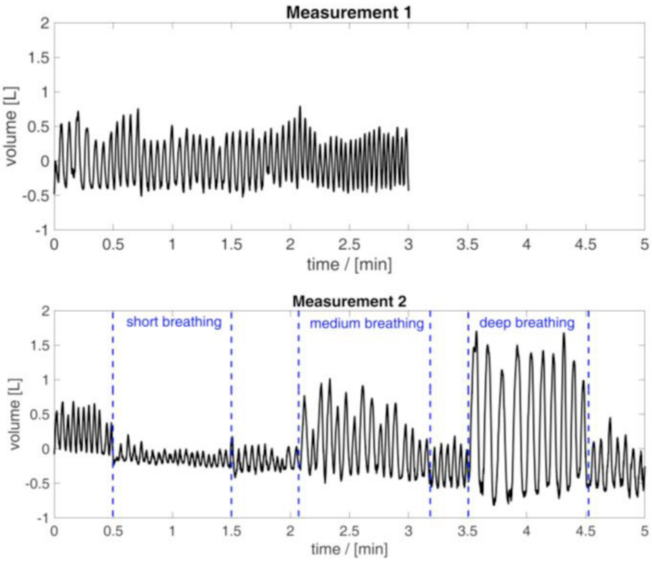

Fig. 4. Volume data obtained by the spirometer during the two measurements (after offset elimination and illustrated based on the data of subject 2). Measurement 1 (top): Normal spontaneous breathing (3 minutes); Measurement 2 (bottom): Breathing of different tidal volumes - periods of short breathing, medium breathing, and deep breathing between short periods of normal spontaneous breathing.

According to Laufer et al. (Laufer et al., 2020a), the participants performed two measurements in each of the three body positions to cover the entire range of tidal volumes. During the first measurement, the participants did three minutes of normal breathing while the motion-tracking device recorded their trunk motions. After a break, the subjects practice several breathing techniques for 60 seconds each (short, normal, moderate, and deep breathing), totaling 5 minutes of recording time.

While the measurements were performed, the subjects' respiration was simultaneously recorded by a spirometer (SpiroScout and LFX Software 1.8, Ganshorn Medizin Electronic GmbH, Niederlauer, Germany). The spirometer was also used to validate the results obtained from the MoCap system.

The measurement details are shown in Figure 4, exemplarily illustrated based on the spirometer volume and subject 2.

2.3 Data Acquisition and Analysis

The MoCap recorded marker positions. The obtained data from each marker represents its motion in space. Figure 5 depicts the schematic of the process followed during measurements and data analysis.

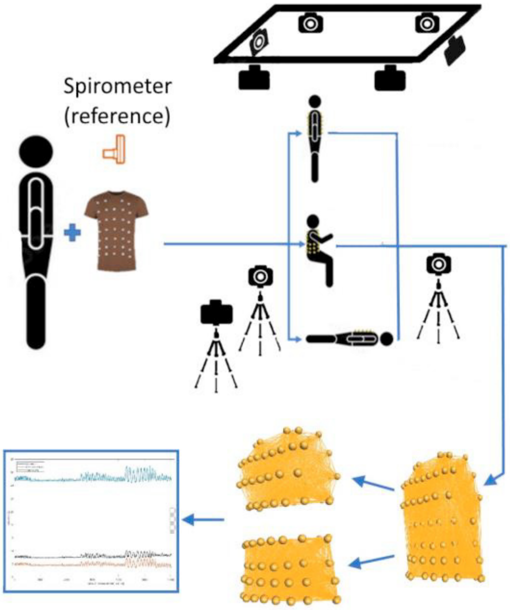

Fig. 5. Schematic representing the process of measurement and data analysis.

Each trial was rebuilt and analyzed to track the movement of the marker and generate the volume flux. MATLAB (R2022a, The MathWorks, Natick, USA) was used to receive data from the VICON Nexus software (Version 1.8.5.6 1009h, Vicon Motion Systems Ltd).

Finally, respiratory volumes were calculated using the *alphaShape* function of MATLAB (*alpha radius* 250 mm), which provided the volume enclosed by the selected MoCap markers.

According to Figure 2 and the anatomy of the subjects, the calculation of the total volume was obtained by using all 102 MoCap markers, while for the thoracic volume, only the MoCap makers from level 0 to level 4 were utilized. Similarly, the abdominal volume was calculated by the *alphaShape* function, using the MoCap markers from levels 4 to 7. Subsequently, the offset was eliminated (*detrend* function of MATLAB). This yielded only the incremental respiratory volume changes of the thoracic and abdominal volumes, which were subsequently analyzed.

Finally, the thoracic percentage [%] and the abdominal percentage [%] were given by

$$\textit{thoracic percentage} = \textit{thoracic volume} / \textit{total volume}$$

and by

$$\textit{abdominal percentage} = \textit{abdominal volume} / \textit{total volume}.$$

3. RESULTS

Table 3 shows the distribution in thoracic and abdominal breathing for all 4 participants in short, normal, and deep breathing, where the participants inhale and exhale the maximum possible. The distribution was obtained in standing, sitting, and lying positions.

Table 3. Summary of thoracic and abdominal percentage of the breath in different positions and during different breathing types.

Breathing Type	Subject	Thoracic percentage [%] / Abdominal percentage [%] of the breath in different positions		
		Sitting	Standing	Laying
Short breathing	1	40 / 60	41 / 59	43 / 57
	2	34 / 66	41 / 59	45 / 55
	3	35 / 65	28 / 72	15 / 85
	4	37 / 63	39 / 61	21 / 79
Normal breathing	1	48 / 52	57 / 43	34 / 66
	2	39 / 61	42 / 58	54 / 46
	3	33 / 67	42 / 58	33 / 67
	4	45 / 55	51 / 49	29 / 71
Deep breathing	1	47 / 53	47 / 53	44 / 56
	2	43 / 57	61 / 39	47 / 53
	3	43 / 57	45 / 55	44 / 56
	4	46 / 54	48 / 52	51 / 49

The distribution in abdominal and thoracic breathing can be seen as well in Figure 6, where the total breathing volume and the abdominal and thoracic volumes are shown based on the data of Participant 4. The sum of abdominal and thoracic volumes is the total breathing volume.

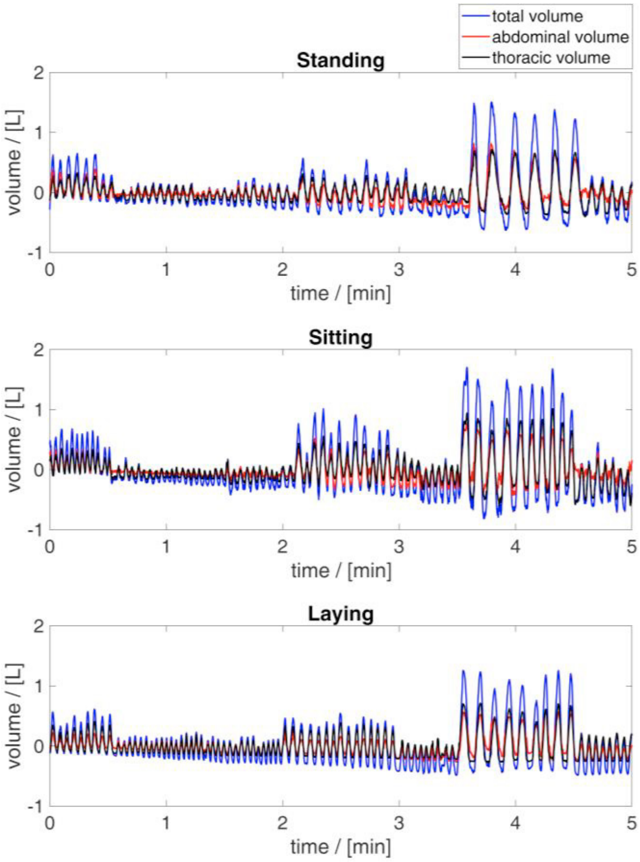

Fig. 6. Example of the distribution between thoracic and abdominal breathing of the breathing volume in standing (top), sitting (middle), and laying (bottom) positions (illustrated based on the data of Participant 4).

4. DISCUSSION

The position of the human body significantly affects pressures on the ribcage, which in turn affects the movement of the intercostal muscles. Goldman et al. (Goldman et al.,1973) referred in their study about estimating the changes in ribcage volume based on changes in its anteroposterior and transverse diameters and how that change is related to transthoracic, transabdominal, and trans-diaphragmatic pressures. The study showed that after applying pressure on the abdominal area via a pneumatic cuff, this compression of the abdomen led to displacing the thoracic pressure and to a trans-diaphragmatic pressure displacement. Our study findings are coherent with their result.

Using the MoCap markers to record the breathing process allows us to distinguish between abdominal breathing and thoracic breathing. The MoCap markers were arranged in 7 layers that cover the areas of the thorax and abdomen, and by separating at level 4, both thoracic breathing volume and abdominal breathing volume can be obtained. The same was calculated for all the measurement positions, which allows the determination of the total tidal volume.

Table 3 shows that during the sitting position, abdominal breathing is dominant, representing between (52% - 67%) of the total normal breathing. The abdominal percentage of breathing increases during shallow breathing and represents between (60% - 66%). However, it decreases during deep breathing to be between (53% - 57%). During the standing position, abdominal breathing decreased and represented between (43% - 58%) in normal breathing, (59% - 72%) in shallow breathing, and between (39% - 55%) in deep breathing. It can be inferred that the percentage of abdominal breathing is significantly higher in the laying position than in other positions. This is due to gravitational forces acting on the thorax and the fact that the chest wall in the posterior region of the torso cannot freely expand and contract during the supine position. It can be assumed that the breathing style is chosen automatically, requiring minor energy/breathing work. Therefore, subjects inhale more air volume through the abdominal region to compensate for the thoracic region.

Our study findings also oppose what (Kaneko et al., 2012) mentioned and show that thoracic breathing is more significant during standing than in other positions. This is also supported by results from (Lalloo et al., 1991). Abdominal breathing is the dominant breathing during the sitting position, which slightly increased while the depth of the breathing increased. Thoracic breathing is not dominant in all three positions, and it reaches the maximum values during standing, where the diaphragm is not pushing up towards the thoracic cavity.

At maximum breaths, participants have no way to divide the breath differently between the chest and abdomen because, at maximum breaths, the body must use the entire capacity of the chest and abdomen. Therefore, maximal breaths could be used to determine the participants' specific maximal volumes of the chest and abdominal breaths.

During lying down in a supine position, abdominal breathing becomes easier where the pressure of the organs becomes minimal, and the movement of the abdomen is becoming easier than moving the complex and rigid structures of the thoracic. Therefore, the percentage of abdominal breathing increases significantly during this position, especially when it comes to shallow breathing; the dependency on abdominal breathing becomes greater.

The division into thoracic and abdominal breathing is individual and varies from person to person. This study was performed on only four subjects and therefore showed no results. Meaningful studies in this area require a large number of participants. However, this study shows a possible trend, which could be confirmed with more participants and different subjects.

Therefore, these measurements should be repeated with more participants of different ages, gender, and body shape to validate the results of this study. Possible lung diseases such as obstructions could also influence the distribution between the chest and abdominal breathing, and this would be another interesting aspect to investigate.

In general, this study will help in the development of intelligent shirts for breath analysis. The dependence of the partition into abdominal and thoracic breathing on body position allows substantial insight into breathing mechanics. It may improve some modeling approaches (Laufer et al., 2020b) and tidal volume measurements based on surface motions of the upper body. This work opens up several avenues for future research into the influence of various other parameters on breathing patterns and how those parameters affect the human body.

5. CONCLUSION

Body posture is one factor affecting respiration, and breathing patterns may vary depending on the body's position and posture. This study showed smaller tidal volumes and lying positions occur when abdominal breathing predominates more. The split between the chest and abdominal breathing is approximately equal at high tidal volumes and in seated or standing situations with no chest dominance.

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AUTHOR'S STATEMENT

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