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Symmetry of Respiration Induced Upper Body Movements

https://doi.org/10.1515/cdbme-2023-1120

Abstract: Many researchers have postulated inexpensive methods to estimate respiratory volumes from respiration-induced movements of the upper body. In the development of smart garments, the number and the optimal positioning of sensors is an essential aspect. Therefore, the symmetry of upper body respiratory movements was investigated based on the measurement data from a motion capture system. In the ventral central area, coefficients of determination above 0.99 regarding movements of symmetrical markers mean that sensors can be placed without restrictions in the position mirrored on the sagittal plane. This simplifies sensor positioning in a smart shirt and expands the range of applications of smart shirts for respiratory monitoring.

Keywords: Upper body symmetry; Tidal volume; Smart clothing; Wearables

1 Introduction

The determination of respiratory volume via respiration-induced surface movements of the upper body has been studied for a long time. Initial attempts and analyses date back to Konno and Mead in the 1960s [1], and despite a variety of alternative approaches [2–5], there has still been no significant breakthrough. These efforts have produced several different measurement methods, some of which are now used sporadically in clinical practice. Most noteworthy is the optoelectronic plethysmography (OEP) [6,7], which analyses upper body movements via a motion capture system (MoCap) to determine respiratory volumes. Unfortunately, the measurement area is restricted to the area between the MoCap cameras, and, thus, the system is not wearable.

Recent research has created the Hexoskin shirt [8]. Studies show that this shirt is capable of providing a range of clinically relevant signals, but has deficiencies in determining respiratory volume [9]. Hence, the determination of tidal volumes is still based on respiratory airflow measurement via spirometry [10,11] or body plethysmography [12].

To support the development of smart shirts, Laufer et al. [13] investigated the respiration-induced movements of the upper body more in detail and evaluated both magnitude and correlation to respiration volume of different movement parameters, such as tilt angles, accelerations, and circumferential changes.

For the development of smart shirts, decisive factors are the type, number and positioning of the sensors used. Some studies addressed these issues [14–17] for inertial measurement units, strain gauges or CiMeD belts [18]. However, in these previous studies, the symmetry of the human body was not taken into account. This work specifically assesses the assumption of symmetry in the upper body as measured across sensors in a smart shirt.

2 Methods

2.1 Measurement setup and participants

The symmetry analysis was carried out using data measured by a MoCap and a spirometer as reference. The MoCap system used (Bonita, VICON, Denver, CO) consisted of nine infrared cameras (VICON Bonita B10, firmware version 404). The cameras monitored the movements of 102 highly reflective MoCap markers, attached to a compression shirt. A schematic sketch of the system and the shirt are illustrated in Figure 1 and Figure 3. A reference tidal volume measurement was

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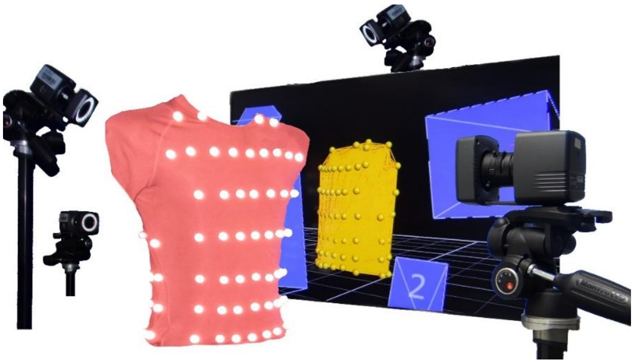

Figure 1: Sketch of the motion capture system and the compression shirt with 102 MoCap markers attached.

provided with a spirometer (SpiroScout, Ganshorn Medizin Electronic GmbH, Niederlauer, Germany).

Five healthy subjects voluntarily participated in the study. The subjects included two women and three men. All participants had no known lung disease. The subjects had a mean height of 1.75 ± 0.03 m, a mean age of 22.2 ± 2.4 years, and a mean weight of 66.2 ± 4.5 kg. All subjects were instructed to undertake the respiratory manoeuvres illustrated in Figure 2. The manoeuvres were designed to capture a broad range of possible tidal volumes. In particular, the participants performed shallow, medium and maximal breaths for approximately one minute each, with normal spontaneous breathing of 30 seconds in between.

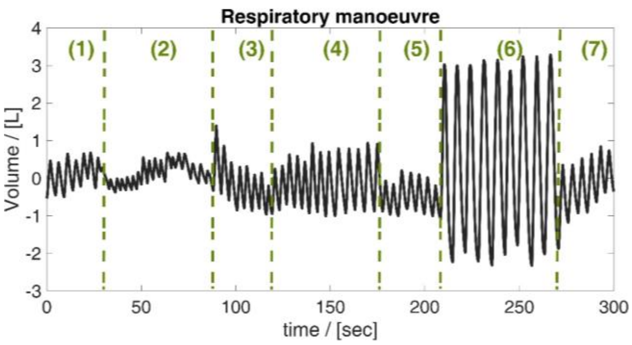

Figure 2: Respiratory maneuver performed by the five subjects. Shallow breathing (2), medium breaths (4) and maximal breaths (6) were done between phases of normal spontaneous breathing (1), (3), (5) and (7).

2.2 Data processing

To investigate symmetry, the correlation of the motion of all MoCap markers along their main motion axis L with their symmetric counterpart $L*$ were analysed (see Figure 3).

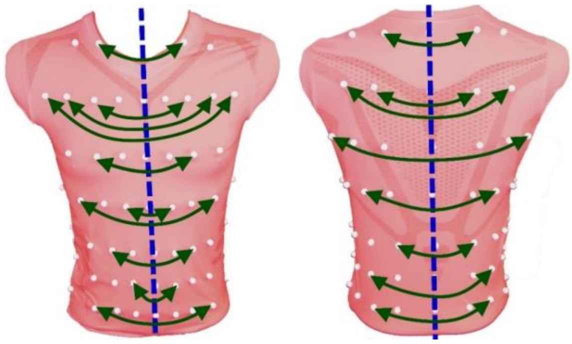

Figure 3: Compression shirt with 102 MoCap markers attached - ventral view (left) and dorsal view (right). The blue dashed line illustrates the axis of symmetry. The green arrows show exemplarily some symmetric MoCap marker pairs, whose correlation to each other was investigated.

The Pearson correlation coefficients were calculated as:

$$R_{L,L^*} = \frac{\sum_{t=t_1}^{t_n}\left(L(t)-\overline{L}\right)\left(L^*(t)-\overline{L^*}\right)}{\sqrt{\sum_{t=t_1}^{t_n}\left(L(t)-\overline{L}\right)^2}\sqrt{\sum_{t=t_1}^{t_n}\left(L^*(t)-\overline{L^*}\right)^2}} \tag{1}$$

Where L is the movement of the selected MoCap marker along its main movement axis (the movement of each marker was projected on its main movement axis), the bar overlay denotes the mean value, $L*$ is the corresponding movement of the symmetric MoCap marker counterpart, and n is the number of measurement points.

The *corrcoef*-function of MATLAB was utilised to obtain the desired correlation coefficients, and the corresponding *p*-values were checked for significance (<0.05). Additionally, the least absolute shrinkage and selection operator (Lasso) [19] and the spirometer reference volume ($\boldsymbol{v}_{spiro}$), was used to determine a set of 4 MoCap markers as an example to evaluate exemplarily the outcomes. The Lasso objective function is defined:

$$\mathbf{x}_{opt,L} = \underset{\mathbf{x}}{\operatorname{argmin}}\left(\left\|\mathbf{A_L}\mathbf{x}-\mathbf{v}_{spiro}\right\|_2+\lambda\|\mathbf{x}\|_1\right) \tag{2}$$

where $\mathbf{A_L}$ is the matrix of the movements of the selected MoCap markers, and λ is the regularisation factor of the penalty term $\|x\|_1$.

Based on the example of the used MoCap marker set, the tidal volumes were modelled by the selected MoCap marker movements $\mathbf{x}_{\text{opt,L}}$ and by their symmetric counterparts $\mathbf{x}_{\text{opt,L*}}$ via:

$$\mathbf{v}_m = \mathbf{A_L}\,\mathbf{x}_{\text{opt,L}} \qquad \text{and} \qquad \mathbf{v}_{m^*} = \mathbf{A_{L^*}}\,\mathbf{x}_{\text{opt,L*}}$$

The volumes $\mathbf{v}_m$ and $\mathbf{v}_{m^*}$ were compared and analysed to investigate the possibility of changing positions of the optimal markers / sensors to their symmetric positions without any restriction.

3 Results

Figure 4 illustrates the correlations of the MoCap marker movements with their symmetrical counterpart. A comparison of the volume curve of the selected marker set and the volume curve based on the mirrored markers set (mirrored on the sagittal plane) is shown in Figure 5.

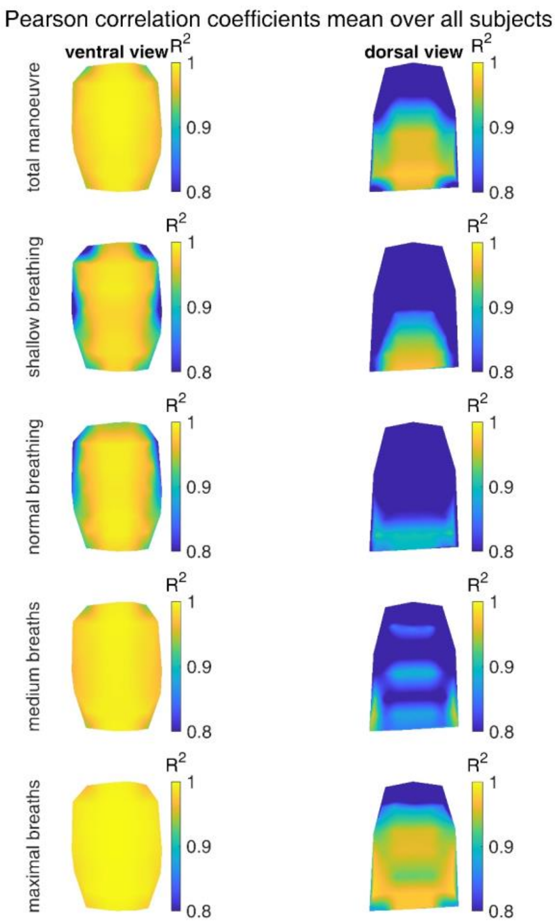

Figure 4: Correlation of the MoCap marker movements with their symmetrical counterpart - ventral view (left) and dorsal view (right) – during the total maneuver (top), shallow breathing, normal spontaneous breathing, medium breaths and maximal breaths (bottom). Note the lower limit for correlation is 0.8.

4 Discussion

Optimal placement of sensors is an important aspect of smart shirt development, and existing symmetries would enormously simplify this. Given symmetrical behaviour of respiratory movements, the symmetrical counterpart of each sensor could be used without restriction, depending on the application or available space on the shirt.

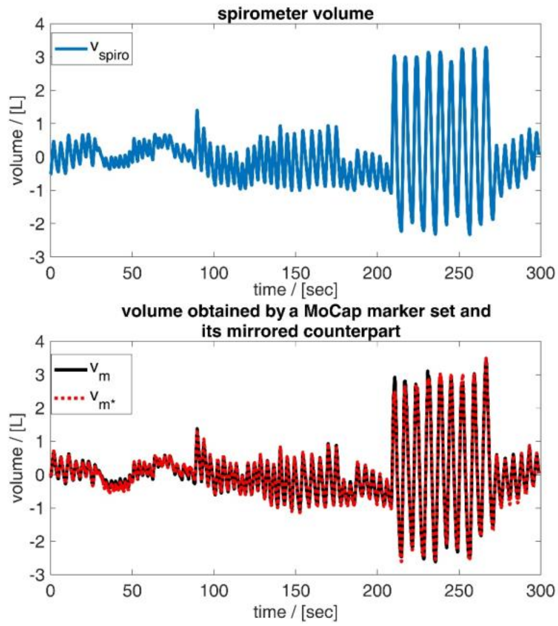

Figure 5: Comparison of the volumes obtained by the optimal MoCap marker set and its mirrored counterpart, exemplarily illustrated based on the data of subject 4.

The external anatomical symmetry of most torsos (thorax) suggest such an assumption is typically valid. However, most organs in the thorax are not symmetrically arranged. Therefore, respiratory movements of the upper body must be checked and analysed for symmetry.

Apart from sensor localisation in smart shirt development, symmetries and, respectively, asymmetries in the upper body during respiration could help to diagnose diseases such as broken ribs, unilateral lung disease, severe atelectasis, emphysema, or pneumothorax [20,21]. However, further studies must analyse subjects with these specific diseases to confirm the potential clinical value of this approach.

A possible symmetrical positioning of sensors in a smart shirt could also increase the area of application or expand the range of patients, as a smart shirt could then be applied to stroke patients or hemiplegic patients by placing the sensors only on the healthy side. This aspect would also need to be evaluated in corresponding studies.

Figure 4 shows that there are very high correlations between MoCap markers ventrally in the central region along the sternum / sagittal plane. Even with low respiratory motion (in the case of shallow breathing) and an associated low signal to noise ratio, high correlations are present. It is evident that the deeper the breaths, the larger the area with high correlations of R^2 above 0.99. In the region of high correlation, markers or sensors can be placed on the other half of the body without restrictions. In the dorsal region, only small respiratory movements occur [13] and thus, probably small, non-respiratory movements contribute to lower correlations.

Figure 5 shows, based on the data of subject 4, the volume curves of the MoCap markers $\mathbf{x}_{opt,L}$ selected by the Lasso method (illustrated in black) and its mirrored MoCap markers of the symmetric counterparts $\mathbf{x}_{opt,L^*}$ (illustrated in red). It can be seen that there are high correlations between spirometer volumes (illustrated in blue) and the volumes of the two marker sets as well as between the two marker sets $\mathbf{x}_{opt,L}$ and $\mathbf{x}_{opt,L^*}$ themselves.

This study covered almost the entire clinically relevant spectrum of respiratory volumes. While care was taken to ensure the shirt was orientated symmetrically on the body, the precision of marker symmetry across the thorax was not measured. Furthermore, all participating subjects were young, healthy, and generally slim. Thus, further studies with more subjects of different ages, genders and body shapes should be performed.

5 Conclusion

In the integration of sensors into a smart shirt, symmetrical properties of the upper body can facilitate optimal positioning of sensors. Especially in the ventral central area, sensors can be placed without restriction in the position mirrored on the sagittal plane. This fact expands the application range of smart shirts for respiratory monitoring, since the sensors can be attached to the healthy side in the case of hemiplegic patients.

Author Statement

Research funding: This research was partly supported by the German Federal Ministry of Education and Research (MOVE, Grant 13FH628IX6) and by the European Commission H2020 MSCA Rise (#872488—DCPM).
Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

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