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Optimal Sensor Location in a Smart-Shirt to Measure Accurate Tidal Volumes During Abdominal and Thoracic Respiration

Abstract: The determination of respiratory parameters via respiration induced surface movements of the upper body has been the subject of research for many years. The displacements of 102 motion capture markers were evaluated in this study in terms of their information content with respect to the tidal volume recorded in parallel using a spirometer. Independent of the breathing types (spontaneous breathing, abdominal breathing, or chest breathing), the number and the location of sensors in a smart shirt to obtain tidal volume information was determined. Only 9 of 102 sensors were sufficient to obtain breathing volume information.

Keywords: Sensor location, Smart-Shirt, Tidal Volumes, Abdominal Breathing, Chest Breathing

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1 Introduction

Obtaining respiratory parameters via surface motions of the upper body has been the subject of research since the 1960s. Having traced the original idea back to Konno and Mead [1], many other studies to date have attempted to determine the desired respiratory parameters via the respiration induced movements of thorax and abdomen. Unfortunately, most of the attempts only achieved moderate success and therefore the determination of respiratory parameters is still based on respiratory flow measurement [2-5], which requires wearing a face mask or breathing through a mouthpiece, while the nose is blocked. For long-term measurements, this can be particularly uncomfortable for the person examined.

The optoelectronic plethysmography (OEP) is a system that allows respiratory parameters to be determined as a function of surface motions of the upper body [6]. The OEP is a suitable method and measures surface motions of the human body accurately. Based on a motion capture system MoCap with multiple cameras an OEP measures the spatial positions of reflective MoCap markers. Unfortunately, the high initial cost and the limitation of the measurement to the area between the cameras prevent a more frequent use.

The potential offered by new and improved sensors and sensor technologies is leading to new ‘smart’ clothing approaches [7, 8]. In the development of smart clothing, the question always arises “*how many sensors are needed? and where they should be placed?*”. This question is addressed in this study for position sensors regarding to abdominal and chest breathing.

2 Methods

2.1 Measurement setup

To analyse the optimal number of spatial position sensors and their location at the upper body, a motion capture system (MoCap) (Bonita, VICON, Denver, CO) with nine infrared cameras (VICON Bonita B10, Firmware Version 404) was used. A total of 102 reflective motion capture markers were placed on a tight compression shirt (48 ventral, 18 lateral and 36 dorsal), which was worn during measurements by the subjects (Fig. 1). The raw data were processed and the spatial positions of all markers at each point in time were transferred by the VICON Nexus Software (Version 1.8.5.6 1009h, Vicon Motion Systems Ltd.) to MATLAB (R2019a, The MathWorks, Natick, USA), for further calculation.

For reference purposes, a spirometer (SpiroScout and LFX Software 1.8, Ganshorn Medizin Electronic GmbH, Niederlauer, Germany) was utilized simultaneously for tidal volume measurement. The SpiroScout supplied flow and volume data and thus, tidal volumes.

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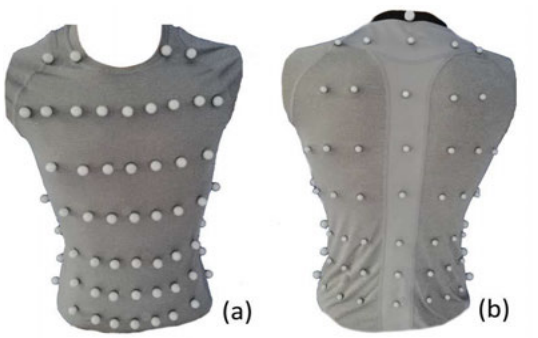

Figure 1: Ventral view (a) and dorsal view (b) of the deployed compression shirt with 102 MoCap markers

2.2 Participants and Respiratory maneuvers

Eight (6 male and 2 female) lung healthy subjects volunteered the measurements in this study. The subjects had an average height of 1.75 m (± 0.06 m), an average weight of 67.4 kg (± 8.4 kg), an average BMI of 21.8 kg/m^2 (± 1.5 kg/m^2) and the average age was 27.0 years (± 11.8 years). Exhaustive subject details can be found in Table 1.

Table 1: Participants.

Subject	Height (m)	Weight (kg)	BMI (kg/m2)	Age (years)	Gender
1	1.84	75	22.2	18	male
2	1.72	65	22.0	19	female
3	1.70	56	19.4	26	male
4	1.67	57	20.4	18	female
5	1.83	78	23,3	30	male
6	1.75	70	22.9	32	male
7	1.79	75	23.4	53	male
8	1.74	63	20.8	20	male

After 3 minutes of normal spontaneous breathing, the subjects performed abdominal und chest breathing, each for about 1 minute (see Table 2) in sitting position. During the measurement, the subjects wore the compression shirt with MoCap markers between the cameras of the MoCap system and performed the desired respiratory manoeuvres. Simultaneously, the respiration was recorded by the spirometer.

Table 2: Respiratory maneuvers.

Approximate duration	Respiration maneuver
180 seconds	normal spontaneous breathing
60 seconds	abdominal breathing
60 seconds	chest breathing

The timing of the respiratory manoeuvres (Table 2) was not strictly prescribed, it was dependent on the subject's breathing rhythm. After the time in the specified breathing pattern had elapsed, the subjects changed the breathing style at the beginning of the next breath.

2.3 Data processing

Fig. 2 illustrates the overall data processing of the study. After projection of the MoCap marker data on their main movement direction, the singular value decomposition (SVD) yielded the number of MoCap markers. The corresponding markers were identified via linear regression in a bootstrapping algorithm.

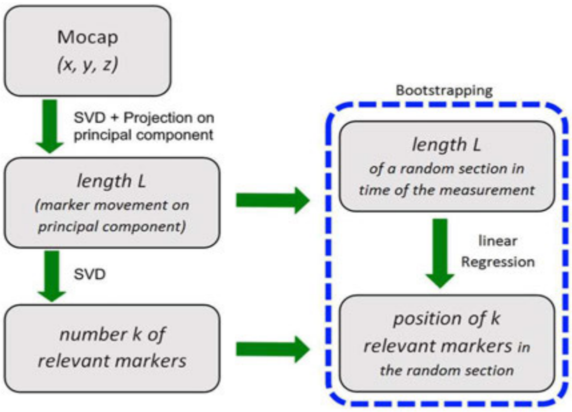

Figure 2: Data processing via Singular Value Decomposition SVD and linear regression

In a previous study [9] was investigated that the movement of individual reflecting MoCap markers was mainly on a particular line. According to this study, a dimension reduction by a projection of the marker positions on this line was performed. For each MoCap marker, its position was projected on the principal component of the marker movement, using SVD [10] and the dot-product in MATLAB. Thus, the movement $(x,y,z)_{t_i}$ of all MoCap markers j in direction of its main principal component (with $1 \leq j \leq 102$), was given by:

$$(x,y,z)_{t_i,j} \approx \left(\overline{x_{MoCap}}, \overline{y_{MoCap}}, \overline{z_{MoCap}}\right)_j + L_{j,t_i} V^*_{1,j}$$

where: L_j is the length of the movement of marker j in the direction of its principal component at time t_i ($1 \leq i \leq n$), based on the mean spatial position value $\left(\overline{x_{MoCap}}, \overline{y_{MoCap}}, \overline{z_{MoCap}}\right)_j$, V_j* is the unit vector of the main principal component of marker j (main principal component of the marker movement) and n is the number of time-points of the measurement.

Thus, the spatial position data of all 102 reflective MoCap markers were transferred into one dimensional length data L, which were arranged in the matrix M:

$$M = \begin{bmatrix} L_{1,t_1} & \cdots & L_{102,t_1} \\ \vdots & \ddots & \vdots \\ L_{1,t_n} & \cdots & L_{102,t_n} \end{bmatrix}$$

Based on this matrix M, the subsequently applied SVD yielded the information content of the system.

$$U\Sigma V^{*} = svd[M]$$

where: U is an orthogonal 102×102 matrix, Σ a diagonal 102×n matrix and V^{*} an orthogonal n×n matrix.

$$\Sigma = \left[\begin{array}{cccc|c} \sigma_1 & 0 & \cdots & 0 & \\ 0 & \sigma_2 & \ddots & \vdots & \\ \vdots & \ddots & \ddots & 0 & 0 \\ 0 & \cdots & 0 & \sigma_{102} & \end{array}\right]$$

The components σ_i ($1 \leq i \leq 102$) on the diagonal of Σ are the singular values of M, which are sorted according to their information content $\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq \ldots \geq \sigma_{102}$.

Thus, the first component σ_1 is carrying the most dominant part of system information, while higher σ usually carrying minor parts of system information and can be neglected.

Analysing the singular values enabled the number of MoCap markers k, needed to obtain the required system accuracy to be determined. Thus, the number of singular values containing more than 2 % of the total system information was identified, which corresponds to the number of required markers / sensors k. The subjects performed the measurement in an upright sitting position. In order to carry out a later movement correction, in which all non-respiratory movements are to be filtered out, three markers were added (cervical, the middle and the lowest spine) to the reduced marker set of k markers. It can be assumed that these additional markers allow such a correction, since all possible non-respiratory movements (rotation and bending forwards and sideways of the upper body) can be detected with these three markers.

Once the number of required markers (k+3) was obtained, a linear regression analysis showed which reflective MoCap markers carried the most informat ion. The markers were identified using the backslash function of MATLAB applied on M and the volume V_{spiro}, measured by the spirometer.

$$\lambda = M \setminus V_{spiro}$$

Subsequently, the resulting vector λ was sorted as higher λ-values of a marker indicate higher influence of this marker on the system. Finally, three markers along the spine and the k markers with the highest λ–values were used for further analysis.

In order to obtain a significantly higher number of data and to reduce the influence of outliers, a bootstrapping algorithm [11] was used to analyse the best sensor positions from each measurement. For this purpose, data from 10,000 randomly selected sections of the measured data were analysed for each subject and it was evaluated how often each marker represented more than 2 % of the system information in each respiratory pattern. Based on the bootstrapping data, the optimal markers were selected from the marker set. These markers largely contributed to the system information and were necessary for further modelling. For more exhaustive details on the data processing data refer to Laufer et al. [9].

3 RESULTS

Across all subjects, the maximal number of MoCap markers required to obtain the required system accuracy was nine. This number was sufficient across the different breathing types. The nine markers included k = 6 distributed across the thorax and three markers along the spine.

Figure 3 shows the information distribution of the markers, regarding the respiratory volume signal obtained by the spirometer, averaged over all subjects attended this study. It illustrates how many times each marker belongs to the markers carrying more than 2 % of respiratory system information.

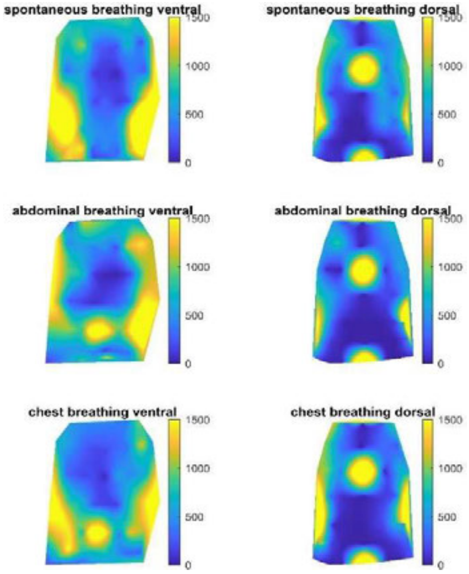

Figure 3: Areas of the shirt, representing the major information content averaged over all subjects, respectively the average how many times each marker location contributes more than 2 % of information to the system regarding respiration. The areas with high information content, where a sensor should be located are illustrated in yellow, while the areas carrying low information are displayed in blue. Ventral view (a) and dorsal view (b).

4 DISCUSSION

Since people breathe with differing ratios of abdominal to thoracic breathing during normal spontaneous breathing a broad set of participants was used in this study. A previous analysis of marker-displacements [12] showed that the displacements of lateral markers of the shirt (Figure 1) are higher than the displacements of the ventral markers and significantly higher than the displacements of dorsal markers during normal and smaller tidal volumes in spontaneous breathing. However, in higher tidal volumes, the dominant displacements occurred in the ventral part of the upper body.

In another previous study [9] the optimal number and location of markers in different tidal volumes according to their information content was analysed, based on 64 MoCap markers in different tidal volumes (from shallow breathing to maximal breaths). In this subsequent study, the focus was on different breathing types (abdominal breathing and chest breathing) and additionally, the number of MoCap markers at the shirt was increased to 102.

Regardless of the higher number of markers, the analysed areas of high information content are consistent with the outcomes of the previous study (see Figure 3 and Figure 4).

The different breath types (spontaneous breathing, abdominal breathing, or chest breathing) only marginally changed the location of the markers carrying information. The arrangement of sensors shown in Figure 4 allow breath information to be determined independent of the different breathing types.

Figure 4: Areas of the shirt, containing the major information content of the system regarding respiration according to [9].

As in the previous study, a clear tendency can be seen that lateral markers dominate at smaller and normal tidal volumes in terms of displacement. Figure 3 shows that lateral markers are also dominant in terms of information content of respiratory volumes, as the area with high information content are in the lateral regions of the upper body.

Nonetheless, in further studies with more participants should be performed in which it should be examined, how the results, obtained in this study, varies with age and body shape of the subjects – that could provide insight into these dependencies.

5 CONCLUSION

The number and location of sensors in a smart shirt necessary to obtain tidal volume information was determined using data sets containing different breath types (spontaneous breathing, abdominal breathing, or chest breathing). Ultimately precise values for breath volume were obtained using only 9 sensors.

Author Statement

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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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