Bernhard Laufer*, Sabine Krueger-Ziolek, Paul David Docherty, Fabian Hoeflinger, Leonhard Reindl and Knut Moeller

Hierarchical Analysis of Thorax Models to Measure Tidal Volume

Abstract: Motion tracking of thorax kinematics can be used to determine respiration. However, determining a minimal sensor configuration from 64 candidate sensor locations is associated with high computational costs. Hence, a hierarchical optimization method was proposed to determine the optimal combination of sensors. The hierarchical method was assessed by its ability to quickly determine the sensor combination that will yield optimal modelled tidal volume compared to body plethysmograph measurements. This method was able to find the optimal sensor combinations, in approximately 2% of the estimated time required by an exhaustive search.

Keywords: spontaneous breathing, body plethysmography, optoelectronic plethysmography, sensor placement, hierarchical analysis

DOI 10.1515/cdbme-2018-0102

1 Introduction

Different approaches are available to monitor spontaneous breathing [1, 2], but in daily practice it is usually monitored via spirometry or body plethysmography [3-5]. However, these methods have some disadvantages such as the requirement for sealed face masks that limit leakage. Thus, the development of a smart shirt equipped with inertial measurement units to record the respiratory parameters of spontaneous breathing would be beneficial.

Recently, specialised clothing has been developed that can measure certain physiological parameters. Novel, improved and miniaturized sensors and sensor technologies enable research and development of novel wearable systems [6-8]. However, in smart clothing the number of sensors should be minimized to reduce the complexity, costs, and the size of the measurement system.

To determine the optimal number and position of sensors on the upper body, precise values of the tidal volume during spontaneous breathing are needed. Optoelectrical plethysmography OEP [9] via a motion tracking system can measure tidal volume during spontaneous breathing. OEP allows the determination of the motion of the upper and lower body caused by breathing efforts. Each OEP marker can be considered an absolute position sensor and through their given position data, the volume enclosed by the nodal points (markers) can be obtained. However, to determine the optimal number and position of sensors, a large number of candidate markers are needed. Redundant markers can be eliminated and the optimal combination of nodal points that delivers the most accurate results for the tidal volume can be determined. However, determining the redundant markers among a large set require immense computational cost. This study introduces an approach to reduce the computational cost needed to determine the optimal combination of sensors.

2 Methods

2.1 Measurement system

The measurement system contained an infrared camera-based motion tracking system (used as an optoelectronic plethysmograph) and a constant-volume body plethysmograph [10] (**Figure 1**).

***Corresponding author: Bernhard Laufer:** Institute of Technical Medicine (ITeM), Furtwangen University, Jakob Kienzle Str. 17, 78054 Villingen-Schwenningen, e-mail: b.laufer@hs-furtwangen.de
Sabine Krueger-Ziolek, **Knut Moeller**: Institute of Technical Medicine, Furtwangen University, Villingen-Schwenningen, Germany
Paul David Docherty: Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand
Fabian Hoeflinger, **Leonhard Reindl:** Department of Microsystems Engineering, University of Freiburg, Freiburg, Germany

The motion tracking-system (Bonita, VICON, Denver, CO) had 9 infrared cameras (VICON Bonita B10, Firmware Version 404) and operated with a sampling frequency of 100 Hz. With help of the VICON Nexus Software (Version 1.8.5.6 1009h, Vicon Motion Systems Ltd.) the data were processed and transferred to MATLAB (R2017a, The MathWorks, Natick, USA) for further processing.

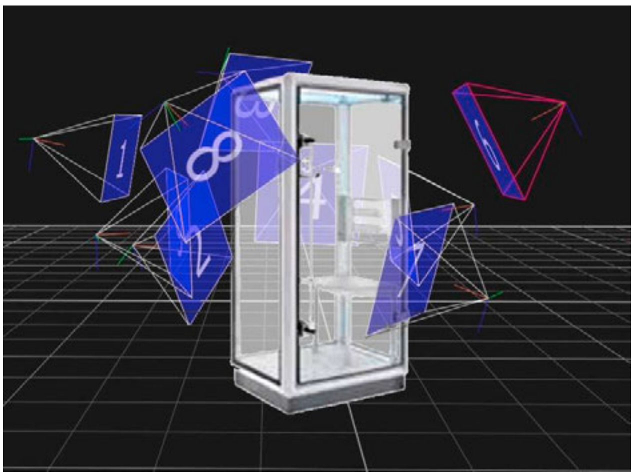

Figure 1: measurement system

The data sampling frequency of the body plethysmograph (PowerCube® Body+, Ganshorn Medizin Electronic, Germany) was 200 Hz for flow and mouth pressure and 400 Hz for the cabin pressure. To record flow and pressure data the LF8 software (Version 8.5M RC25r7071, Ganshorn Medizin Electronic GmbH) was used. Via the serial port the raw data were monitored.

64 motion tracking markers were attached to a compression shirt (size S) (**Figure 2**). 32 markers ventral, 6 markers lateral and 26 markers were placed dorsal in 5 different transverse planes in different heights.

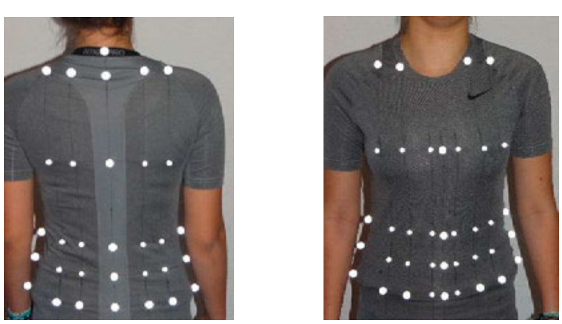

Figure 2: compression shirt with motion tracking markers (front view (left) and back view (right))

2.2 Data

Two male and one female volunteers were wearing the compression shirt while they did some normal breathing, deeper breathing, shallow breathing and three maximal breaths inside the body plethysmograph.

2.3 Data processing

The combinatorics indicate that the number n of all combinations of 64 sensors is

$$n = 2^{64} \approx 1.8 \cdot 10^{19}$$

and all combinations of i sensors in a group of 64 sensors is

$$\binom{64}{i}.$$

Hence, the computational cost to analyse all sensor placement combinations is enormous. Anatomical constraints imply that 5 sensors along the spine had to be considered essential. In each set of sensors, these 5 sensors should be included to be able to eliminate noise from the respiratory signal due to movements of the upper body that are not related to respiration. Hence, the set of candidate position locations could be reduced to 64-5=59. Hence, the number of all combinations of 59 sensors is n_1=5.76·10^{17} and the number of all combinations of i sensors is

$$\binom{59}{i}.$$

Thus, the number of combinations of 3 sensors was

$$\binom{59}{3} = 32{,}509 .$$

2.4 Hierarchical reduction

Of 32,509 combinations of a set of i=3 sensors, only the best m combinations, which provide the smallest mean error for the tidal volume, were taken into account for further processing. The *alphaShape* function of MATLAB with an *alphaRadius* of 250 was used to obtain the volume V_{model}, based on the data points of the motion tracking system. The volume data V_{body} and V_{model} were utilized to determine the tidal volumes $V_{T,body}$ and $V_{T,model}$.

$$Error = V_{T,body} - k_1 \cdot (V_{T,model} - k_2) \quad (1)$$

where: $V_{T,body}$ is the tidal volume obtained by the body plethysmograph, $V_{T,model}$ the tidal volume obtained by the motion tracking system and k_1 and k_2 are correction parameters.

Afterwards, one sensor after another from the remaining sensor-set of (64-5-3=56) sensors was temporary added to the chosen 5+3 sensors. This was iterated for all sets of *i* sensors. For each new combination of i+1 sensors, the tidal volume estimation error was calculated and only the best m combinations were taken for further calculation. Thus, the calculation costs were reduced enormously to n_2.

$$\begin{aligned} n_2 &= 32{,}509 + m \cdot 56 + m \cdot 55 + \ldots + m \\ &= 32{,}509 + m \sum_{i=1}^{56} i \\ &= 32{,}509 + m \cdot 1596 \end{aligned}$$

Setting m to 1000, which means only the best 1000 sensor combinations for each i sensors are taken for further processing, the number of calculations were reduced from $n_1=5.76 \cdot 10^{17}$ to n_2=1,628,509.

To evaluate the hierarchical calculation, we trimmed the sensor-set down to 28 sensors, according to anatomical constraints, where again the 5 mentioned sensors (along the spine) were indispensable and all 8,388,608 combinations of the remaining 23 sensors were analysed. Consequently, the computational costs were manageable, and the results could be compared with the hierarchical approach.

3 Results

The mean error for tidal volume calculation is shown in Figure 3 for all sensor combinations (solid lines) and for the hierarchical approach (dotted lines) using m=1000.

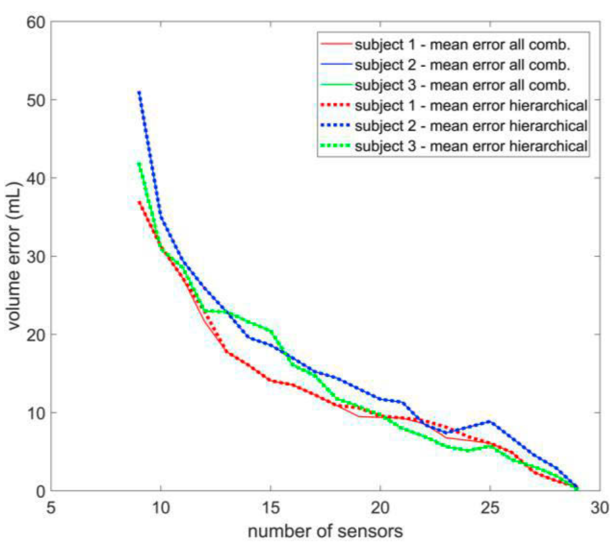

Figure 3: Mean error of best models for all combinations and for the hierarchical approach, based on *m*=1000

In Table 1 the chance to find the best sensor combination with the hierarchical approach is given for different m.

Table 1: Chance to find the optimal sensor combination by the hierarchical approach

m	n_2	subject1	subject2	subject3
50	43,009	33%	29%	33%
100	53,509	38%	52%	42%
200	74,509	62%	76%	48%
500	137,509	62%	85%	48%
1000	242,509	67%	100%	100%
2000	452,509	100%	100%	100%

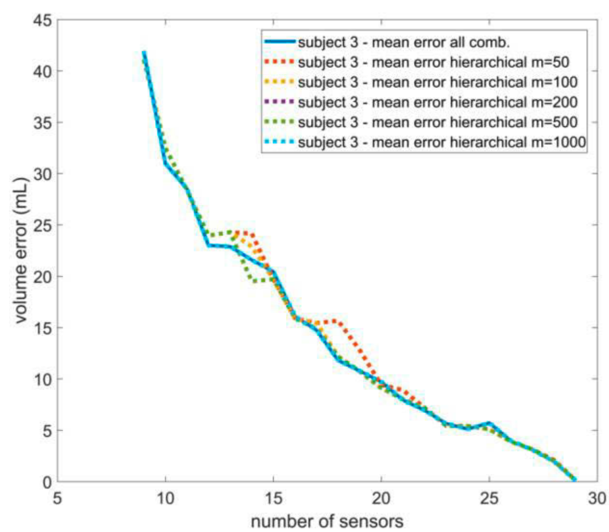

Figure 4: Mean error of best sensor combination for different m in the hierarchical approach for subject 3.

4 Discussion

The computational effort to analyse exhaustively to search all possible combinations of 64 sensors is immense. However, ierarchical approach provided the opportunity to obtain the desired data with much lower computational cost. The method is based on the hypothesis that there are favourable chances of obtaining the best combination of $i+1$ sensors by adding 1 sensor to the m best combination of i sensors, assumed that m is big enough. Thus, complexity of the computational costs is reduced from $O(2^n)$ to $O(n^2)$, where n is the number of sensors.

In this study the number of used sensors was significantly reduced to 28, being able to calculate the tidal volume error of all sensor combinations as a reference. Afterwards, the hierarchical approach was applied successfully.

For smaller m there was a lower chance to find the ideal combinations. For example, when m=50, the chance of getting the optimal sensor-set was about 30%. In contrast, for m=1000, the optimal sensor-combinations was found by this method 100% of the time for two of the three subjects. For subject 1 with m=1000, the optimal sensor sets were found in only 67% of cases. Thus, increasing m to 2000 the approach was able to get all (100%) optimal combinations.

However, even if the best model is not found, the mean error for the tidal volume determination in **Figure 3** and **Figure 4** shows, that this error is not significantly higher in cases when the optimal sensor combination was not found. The mean error of the next best sensor combinations was generally comparable and still small. Hence, even at low m values, the volume estimation error remained within acceptable tolerances for clinical value.

5 Conclusion

The hierarchical approach is suitable to analyse the minimal and best combination of each number of sensors in the sensor-set, if the calculation parameters are chosen adequately. Thus, the computational effort can be reduced enormously.

Acknowledgment: This research was partly supported by the MWK Baden-Württemberg, “ReDMON” – Innovative Projekte.

Author’s Statement

Research funding: As mentioned in the Acknowledgments public funded grants are involved. 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.

References

[1] Wanger J, Clausen JL, Coates A, Pedersen OF, Brusasco V, Burgos F, Casaburi R, Crapo R, Enright P, *et al.* Standardisation of the measurement of lung volumes. European Respiratory Journal 2005; 26 (3): 511.

[2] Heyde C, Leutheuser H, Eskofier B, Roecker K, Gollhofer A. Respiratory inductance plethysmography-a rationale for validity during exercise. Medicine and science in sports and exercise 2014; 46 (3): 488-495.

[3] Miller MR, Hankinson J, Brusasco V, Burgos F, Casaburi R, Coates A, Crapo R, Enright P, van der Grinten CP, *et al.* Standardisation of spirometry. Eur Respir J 2005; 26 (2): 319-38.

[4] Hayes D andKraman SS. The physiologic basis of spirometry. Respiratory care 2009; 54 (12): 1717-1726.

[5] Criée CP, Sorichter S, Smith HJ, Kardos P, Merget R, Heise D, Berdel D, Köhler D, Magnussen H, *et al.* Body plethysmography – Its principles and clinical use. Respiratory Medicine 2011; 105 (7): 959-971.

[6] Aliverti A. Wearable technology: role in respiratory health and disease. Breathe (Sheff) 2017; 13 (2): e27-e36.

[7] Heyde C, Mahler H, Roecker K, Gollhofer A. A wearable respiratory monitoring device--the between-days variability of calibration. Int J Sports Med 2015; 36 (1): 29-34.

[8] Gaidhani A, Moon KS, Ozturk Y, Lee SQ, Youm W. Extraction and Analysis of Respiratory Motion Using Wearable Inertial Sensor System during Trunk Motion. Sensors (Basel) 2017; 17 (12).

[9] De Groote A, Wantier M, Cheron G, Estenne M, Paiva M. Chest wall motion during tidal breathing. J Appl Physiol 1985; 83 (5): 1531-7.

[10] Laufer B, Krueger-Ziolek S, Moeller K. Sensorpositionierung bei einem Smart-Shirt zur Atemanalyse bei Spontanatmung. AUTOMED 2018 (Automatisierungstecchnische Verfahren für die Medizin) Villingen-Schwenningen 2018; 48 – 50.