Bernhard Laufer*, Paul D. Docherty, Nour Aldeen Jalal, Sabine Krueger-Ziolek, Fabian Hoeflinger, Leonhard Reindl, Knut Moeller

Tiffeneau-Testing by means of a Smart-Shirt

https://doi.org/10.1515/cdbme-2022-1157

Abstract: Tiffeneau manoeuvres are an important method in pulmonary function testing of the human lungs and can help to diagnose respiratory obstructions. Data from a motion capture system and a spirometer was used to evaluate Tiffeneau indexes which can theoretically be derived via a Smart-Shirt that incorporates three circumference measurements of the upper body. The mean error was 4.5% regarding the Tiffeneau indexes gained by the spirometer, indicating that clinical diagnosis of obstruction is potentially possible using a Smart-Shirt.

Keywords: Tiffeneau test, Wearables, Smart Clothing.

1 Introduction

Pulmonary function tests (PFT) of human lungs have long been an important component of medical diagnostics and therapeutic monitoring. At the appearance of any pulmonary disease, PFTs are normally the first medical examination procedure - they are usually done via spirometry [1] or body plethysmography [2]. Especially during the Corona pandemic, the importance of PFT is once again evident and shows that these examination methods not only have their justification, but are gaining further importance.

Tiffeneau tests are an essential part of PFT. In medical practice, Tiffeneau tests are a good way to diagnose airflow obstructions, such as in chronic obstructive pulmonary disease COPD [3]. It is an old and simple method and can be performed during spirometry or body plethysmography. Via Tiffeneau tests, a dynamic respiratory parameter, the forced expiratory volume in one second (FEV1) can be determined as well as the forced vital capacity (FVC) which indicates how much air the person can exhale maximally. The ratio between these two parameters FEV1/FVC is called Tiffeneau-Pinelli index [4]. A Tiffeneau-Pinelli index in clinical examinations of less than 0.70 indicates a possible obstructive disorder [5], and frequently leads to more intensive diagnostic tests.

Recent progress in the development of new or improved sensors or sensor technologies has led to efforts to find an alternative to flow measurements, such as spirometry or body plethysmography. Some alternative approaches are based on inertial measurement units [6], strain gauges [7] or systems, based on circumference measurements at the upper body [8]. Since prior examinations showed that circumferential measurements on the upper body carry a large part of respiratory information, the present study evaluates whether such an approach could theoretically be used to perform Tiffeneau tests by means of a low-cost Smart-Shirt and could find potential application in medicine.

2 Methods

2.1 Measurement setup

In accordance to Laufer et al. [9] the measurement setup included a motion capture system MoCap (Bonita, VICON, Denver, CO) (see Figure 1) with nine infrared cameras (VICON Bonita B10, Firmware Version 404) and a spirometer (SpiroScout and LFX Software 1.8, Ganshorn Medizin Electronic GmbH, Niederlauer, Germany). Subjects performed a Tiffeneau test (see Figure 2) via the spirometer, while they wore a compression shirt with 102 MoCap markers, and were surrounded by the MoCap cameras.

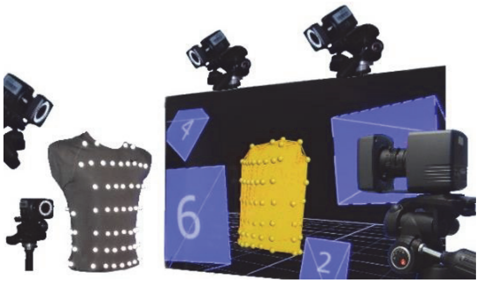

Figure 1: Schematic sketch of the MoCap system and the shirt with 102 MoCap markers.

***Corresponding author: Bernhard Laufer:** Institute of Technical Medicine (ITeM), Furtwangen University, Villingen-Schwenningen, Germany, b.laufer@hs-furtwangen.de
Nour Aldeen Jalal, Sabine Krueger-Ziolek, Knut Moeller: ITeM, Furtwangen University, Villingen-Schwenningen, Germany
Paul D. Docherty: University of Canterbury, Christchurch, New Zealand
Fabian Hoeflinger, Leonhard Reindl: University of Freiburg, Freiburg, Germany

The MoCap system captured the respiration induced surface motions of the upper body during the test and the volume obtained by the spirometer was used as reference value. For more details regarding the measurement setup, please refer to Laufer et al. [9].

2.2 Participants / Respiratory maneuvers

Six male and two female lung-healthy subjects voluntarily participated in the measurements. A written informed consent was obtained from each subject. The subjects were told that in case of any inconvenience they could stop the study at any time. All measurements were made in accordance with the tenets of the Helsinki Declaration and were made as pleasant as possible for the subjects.

The subjects were in average 27.0 ± 4.2 years old, the weight was 67,4 ± 3.0 kg and the height was 1.75 ± 0.02 m. These values describe the mean values over all subjects and the standard errors. For more details on the subjects, please refer to Table I.

TABLE I. DETAILS OF THE PARTICIPANTS

Subject	Height (m)	Weight (kg)	BMI (kg/m^2)	Age (years)	Gender
1	1.84	75	22.15	18	male
2	1.72	65	21.97	19	female
3	1.70	56	19.38	26	male
4	1.67	57	20.44	18	female
5	1.83	78	23.29	30	male
6	1.75	70	22.86	32	male
7	1.79	75	23.41	53	male
8	1.74	63	20.81	20	male

The subjects performed a Tiffeneau test. During a Tiffeneau test, a phase of normal spontaneous breathing is followed by a maximum exhalation. This is followed by a maximum inhalation. Then the air in the lungs is exhaled as forcefully and rapidly as possible to the point of maximal exhalation.

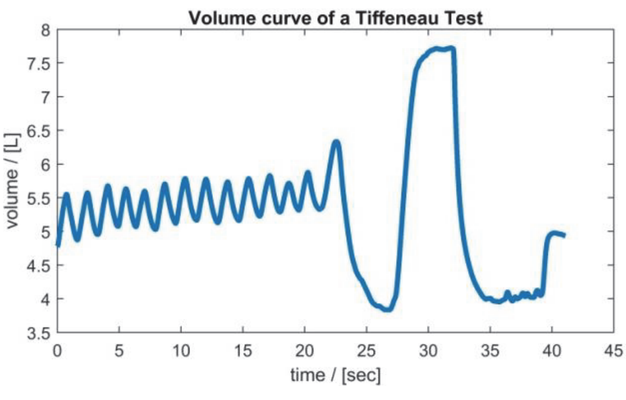

Figure 2: Volume curve obtained during a Tiffeneau test illustrated based on the spirometer data of subject 2.

An exemplar volume curve from a Tiffeneau test measured by the spirometer is illustrated in Figure 2.

2.3 Data processing

Based on the MoCap data, and as a theoretical substitute for taking measurements using a smart shirt, three circumferential changes on the upper body were calculated. The circumferences were obtained by using closed spline curves through all the MoCap markers in the same height at the upper body. One circumference was in the transverse plane in the height of the thoracic vertebra T3, the second in the transverse plane caudal under the scapula in height of T7 and the third around the body in the transverse plane in the height of the lumbar vertebra L1. Since the exact heights of the circumferences could vary depending on the body shape of the subjects, the description of the heights is only an approximation.

Subsequently, a linear regression model was used to determine tidal volumes from the calculated circumferences (**C**). The regression parameters **λ** were obtained from spirometry volume ($\mathbf{v_s}$) by:

$$\boldsymbol{\lambda} = (\mathbf{C}^T \mathbf{C})^{-1} \mathbf{C}^T \mathbf{v_s}$$

Then the volume ($\mathbf{v_c}$) was derived fully from the three circumferential changes by:

$$\mathbf{v_c} = \mathbf{C}\, \boldsymbol{\lambda}$$

Additionally, the volume enclosed by all 102 MoCap markers ($\mathbf{v_{MC}}$) was determined (*alphaShape* function of MATLAB (R2021a, The MathWorks, Natick, USA)).

Finally, the obtained volumes $\mathbf{v_s}$, $\mathbf{v_c}$, and $\mathbf{v_{MC}}$ were used to identify the desired Tiffeneau indexes.

3 Results

The volume curves of a Tiffeneau test with different measurement methods are shown in Figure 3. Figure 4 shows the same curves, limited to the area of forced expiration, which is used to determine FEV1 and FVC. The determined values for FEV1 and FVC are shown in Table 2 and the calculated Tiffeneau indexes in Table 3.

The mean error of the Tiffeneau indexes obtained by measuring three circumferential changes was 4.5% compared to the Tiffeneau indexes resulting from spirometry, whereas Tiffeneau indexes resulting from the MoCap system showed deviations of 4.2%.

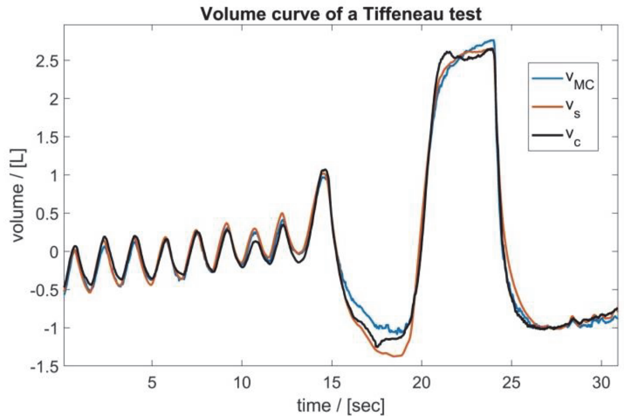

Figure 3: Volume curves (spirometer (red), MoCap system (blue) and Model based on 3 circumferences (black)) obtained during a Tiffeneau test. These curves are illustrated based on the data of subject 2.

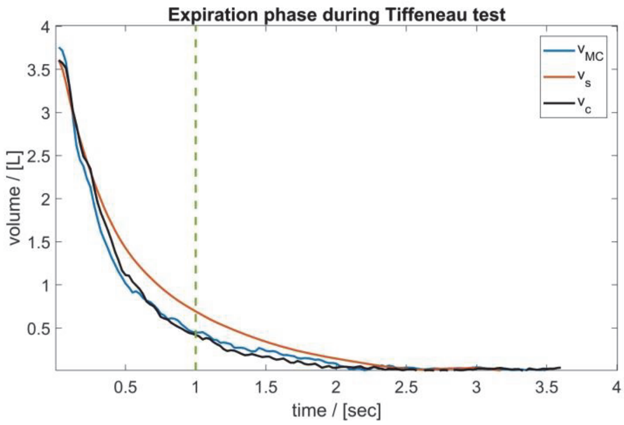

Figure 4: Volume curves of Figure 3 restricted to the forced exhalation during the Tiffeneau test. The green dashed line indicates one second after the start of exhalation, at which the volume curve delivers FEV1 (subject 2).

TABLE 2: FEV1 and FVC (in liters) obtained by the spirometer, the MoCap system and by the model based on three circumferences.

Subject	FEV1 / FVC Spirometer	FEV1 / FVC MoCap	FEV1 / FVC Model circ.
1	3.9 L / 4.6 L	3.4 L / 4.0 L	4.0 L / 4.7 L
2	2.9 L / 3.6 L	3.3 L / 3.8 L	3.2 L / 3.6 L
3	3.3 L / 3.9 L	2.3 L / 2.8 L	3.1 L / 3.7 L
4	2.1 L / 2.9 L	2.4 L / 3.0 L	2.1 L / 3.2 L
5	4.5 L / 5.9 L	3.5 L / 4.9 L	4.3 L / 5.9 L
6	4.0 L / 4.8 L	3.7 L / 4.3 L	4.5 L / 5.1 L
7	3.1 L / 4.3 L	2.4 L / 3.4 L	2.5 L / 3.6 L
8	3.5 L / 4.2 L	3.4 L / 4.2 L	3.5 L / 4.5 L

Table 3: Tiffeneau index by the spirometer, the MoCap system and by the model based on three circumferences

Subject	Tiff.- Index Spirometer	Tiff.- Index MoCap	Tiff.- Index Model circ
1	0.84	0.83	0.85
2	0.81	0.88	0.88
3	0.85	0.84	0.86
4	0.72	0.79	0.66
5	0.75	0.72	0.73
6	0.83	0.87	0.88
7	0.71	0.69	0.68
8	0.82	0.82	0.77

4 Discussion

There are several reasons to look for an alternative to flow measurement during spirometry or body plethysmography. On the one hand, flow measurement requires breathing through a mouthpiece or breathing mask, which can become uncomfortable over time, and breathing through a mouthpiece, can influence the measurement results itself. A more convenient way would be to measure tidal volumes via a Smart-Shirt, by analysing upper body surface motions.

In pulmonary function tests, the true physiological parameters are sometimes impossible to determine. Most spirometers and body plethysmographs use flow sensors that can accurately measure laminar air flows under laboratory conditions. However, these high accuracies cannot necessarily be achieved in measurements with patients in clinical conditions. In addition, test precision is often dependent on the cooperation of the patient, which further complicates a determination of the true parameters. For these reasons, medical professionals generally prefer to rely on relative values. Relative values can compensate for some inaccuracies or systematic errors if both the measured value and the reference value were measured with the same device. However, even though the true reference value for many respiratory parameters cannot be measured, the spirometer is usually considered as gold standard and used as a reference.

A Tiffeneau index represents one of these relative values in PFT. The Tiffeneau test is easy to perform and allows the determination of important dynamic respiratory parameters FEV1 and FVC. FEV1 is an indicator how fast the person can exhale and if any obstruction is present, while FVC is the amount of air, which can be forcefully exhaled in total.

The mean error of Tiffeneau indexes (ratio: FEV1/FVC) over all 8 subjects was 4.5% between the spirometer and circumferential model-based volumes. These deviations are within the bounds of clinically relevance and demonstrate that it is theoretically possible to determine Tiffeneau indexes via a Smart-Shirt.

Previous studies showed that volumes obtained by the MoCap system showed higher deviations at deep breaths [10]. This effect also occurred in this study during the Tiffeneau tests. At deep breaths, tidal volumes measured by the MoCap system were lower than tidal volumes by the spirometer. This could be caused by the compression of the air in the lungs, since significantly higher pressures are generated at maximal breaths. The volume measured by the spirometer is not affected by compressions. Hence, this aspect could explain the deviations of the Tiffeneau indexes gained by surface motions of the upper body compared to the spirometer data.

Some Tiffeneau indexes in this study were less than 0.7, which could indicate a kind of airway obstruction, but Tiffeneau testing is highly dependent on subject compliance and effort. In clinical settings, patients are strongly motivated by trained personnel to obtain meaningful results. Since our study did not focus on a medical diagnosis, but evaluated the results of three different devices during a Tiffeneau test, the diagnostic potential of the values was not of major interest. In contrast, the comparison between the devices was decisive. However, despite the small errors, two subjects were misdiagnosed with the alternative system, regarding the given threshold of 0.7. This fact should be examined in more detail with a higher number of participants.

The tight fit of the shirt could be a limitation for clinical use in critically ill patients. This also needs to be investigated in more detail. However, other diagnostic devices involve higher burdens for the patient in this respect (e.g. the tight fit electrode belt during electrical impedance tomography).

Furthermore, studies with more participants should be conducted to confirm these results. Additionally, the robustness to overfitting could be evaluated in further studies and studies with COPD patients could show whether obstructions can also be detected robustly and reliably with Smart-Shirts. In all further studies, repeated Tiffeneau tests (several times) would support evaluation. If Tiffeneau indexes can be reliably identified, the clinical use of Smart Shirts will increase significantly, as these clinically relevant respiratory parameters play an essential role in the diagnosis of obstructions.

5 Conclusion

Tiffeneau testing can be done by means of a Smart-Shirt. Smart-Shirts measuring changes in three circumferences on the upper body are able to determine Tiffeneau indexes with a level or precision that would allow clinically relevant conclusions. Hence, the Smart-Shirt should be specifically tested to determine its potential used for diagnosing respiratory obstruction.

Author Statement

Research funding: This research was partly supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWi) (ZIM-Grant KK5151903BM1) and 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.

References

[1] M. R. Miller et al., ‘Standardisation of spirometry’, Eur Respir J, vol. 26, no. 2, pp. 319–38, 2005.
[2] C. P. Criée et al., ‘Body plethysmography – Its principles and clinical use’, Respiratory Medicine, vol. 105, no. 7, pp. 959–971, 2011, doi: http://dx.doi.org/10.1016/j.rmed.2011.02.006.
[3] J. L. López-Campos, W. Tan, and J. B. Soriano, ‘Global burden of COPD.’, Respirology, vol. 21, no. 1, pp. 14–23, Jan. 2016, doi: 10.1111/resp.12660.
[4] S. P. Bhatt et al., ‘Discriminative Accuracy of FEV1:FVC Thresholds for COPD-Related Hospitalization and Mortality.’, JAMA, vol. 321, no. 24, pp. 2438–2447, Jun. 2019, doi: 10.1001/jama.2019.7233.
[5] J. Vestbo and P. Lange, ‘Accuracy of Airflow Obstruction Thresholds for Predicting COPD-Related Hospitalization and Mortality: Can Simple Diagnostic Thresholds Be Used for a Complex Disease?’, JAMA, vol. 321, no. 24, pp. 2412–2413, Jun. 2019, doi: 10.1001/jama.2019.6584.
[6] G. Karacocuk et al., ‘Inertial Sensor-Based Respiration Analysis’, IEEE Transactions on Instrumentation and Measurement, pp. 1–8, 2019, doi: 10.1109/tim.2018.2889363.
[7] M. Chu et al., ‘Respiration rate and volume measurements using wearable strain sensors’, npj Digital Medicine, vol. 2, , Art. no. 1, Feb. 2019, doi: 10.1038/s41746-019-0083-3.
[8] B. Laufer, S. Krueger-Ziolek, P. D. Docherty, F. Hoeflinger, L. Reindl, and K. Moeller, ‘An Alternative Way to Measure Tidal Volumes’, in 8th European Medical and Biological Engineering Conference, Cham, 2021, pp. 66–72.
[9] B. Laufer et al., ‘Optimal Sensor Location in a Smart-Shirt to Measure Accurate Tidal Volumes During Abdominal and Thoracic Respiration’, Current Directions in Biomedical Engineering, vol. 7, no. 2, pp. 574–577, 2021, doi: doi:10.1515/cdbme-2021-2146.
[10] B. Laufer, J. Kretschmer, P. D. Docherty, K. Möller, F. Höflinger, and L. Reindl, ‘Sensor placement in a smart compression shirt to measure spontaneous breathing’, Biomed Tech, vol. 62(Suppl.1), p. S127, 2017.