Simon Beck*, Bernhard Laufer, Sabine Krueger-Ziolek and Knut Moeller

Measurement of respiratory rate with inertial measurement units

Abstract: Demographic changes and increasing air pollution entail that monitoring of respiratory parameters is in the focus of research. In this study, two customary inertial measurement units (IMUs) are used to measure the breathing rate by using quaternions. One IMU was located ventral, and one was located dorsal on the thorax with a belt. The relative angle between the quaternion of each IMU was calculated and compared to the respiratory frequency obtained by a spirometer, which was used as a reference. A frequency analysis of both signals showed that the obtained respiratory rates vary slightly (less than 0.2/min) between the two systems. The introduced belt can analyse the respiratory rate and can be used for surveillance tasks in clinical settings.

Keywords: respiratory rate, inertial measurement unit, quaternions, spontaneous breathing

https://doi.org/10.1515/cdbme-2020-3060

1 Introduction

Due to the demographic change of the population and the increasing air pollution, a rising number of people is suffering from respiratory diseases. These facts lead to an increasing need for monitoring lung function. Depending on the goal of monitoring, there is a variety of respiratory parameters to choose from, starting with respiratory rate to tidal volume. These diverse monitoring aspects need different kinds of measurement systems [1, 2]. Gold standards for pulmonary function tests are spirometry and body plethysmography, which are both used in medical examinations. In both systems, the patient must breathe through a mouthpiece or a face mask with a sealed nose. This can be very uncomfortable during long term measurements or even impossible for older people, children, or people with pre-existing disease conditions in general.

First initial approaches measuring respiratory parameters by focusing on movements of the thorax are dated back to the middle of the 20th century [3]. This topic is still a matter of research, as a real breakthrough mainly refers to tidal volume measurement did not occur. And even recent studies, based on IMUs or strain gauges, with similar aims, did show a strong dependency on the sensor placement on the patients [4] or problems with motion artefacts [5].

The focus of this study was respiratory rate measurement via IMUs that record thorax movements during breathing. Two low-cost sensors were used to analyse the respiratory rate in an accuracy, sufficient for surveillance tasks in homecare or some clinical settings.

2 Methods

2.1 Measurement setup

In this study, two customary, low-cost 3-axis-gyroscopes and accelerometers (MPU6050, InvenSenseTM, San José, California, USA) on a breakout board (GY-521) were connected to an Arduino MKR1010 Board (ARDUINO.CC und Arduino IDE Version 1.8.8) where their data could be recorded. Subsequently, the data was processed via MATLAB (R2019a, The Math Works, Natick, USA).

To make sure that movements of the upper body, which are not induced by respiration, can be compensated one IMU was placed on the front, one on the back of the thorax in the height of the xiphoid process of the sternum (Figure 1). The thoracic movement was detected based on the respiration dependent changes of the angle between ventral and dorsal IMU. We were assuming, that movements which are not respiration induced, change the global quaternions of the ventral and the dorsal IMU in the same way, but not the angle between them. While a single IMU would not allow movement artefacts to be corrected, more than two IMUs would increase the complexity of the system [6], which

***Corresponding author: Simon Beck:** Institute of Technical Medicine, Furtwangen University, Jakob-Kienzle-Straße 17, Villingen-Schwenningen, Germany, simon.beck@hs-furtwangen.de
Bernhard Laufer, Sabine Krueger-Ziolek, Knut Moeller, Institute of Technical Medicine, Furtwangen University, Villingen-Schwenningen, Germany,

should be kept as simple as possible for very cost-effective applications.

As a reference system, a spirometer (SpiroScout® / LFX Software 1.8, Ganshorn Medizin Electronic GmbH, Niederlauer, Germany) was used. The measurements with both systems were carried out simultaneously.

2.2 Study design / Participants

Five test persons were equipped with the IMU-belt (Fig. 1) and breathed through the spirometry mouthpiece while wearing a nose clip. Three different breathing rates are measured each for approximately 30 seconds. The subjects were told to start with a normal breathing rate, followed by slightly faster breathing and finally ending up in fast breathing. The exact breathing rates differed amongst the subjects and were chosen by the subjects themselves. For security reasons, the subjects were told, in case they feel any discomfort during the measurement, eventually caused by hyperventilation, to stop the measurement.

During the measurement, the subjects were sitting on a chair and were advised to breathe deeply and focus on thoracic respiration. The belt was attached in the height of the xiphoid process of the sternum and, therefore, the belt would not be sensitive to respiration induced movements of the abdomen during pure abdominal breathing.

Table 1 shows detailed characteristics of the 5 subjects which were measured while performing the above-described breathing manoeuvre.

Table 1: *Participants.*

subject	height [cm]	weight [kg]	BMI [kg/m²]	Age [years]	gender
1	175	72	23.5	31	Male
2	170	59	20.4	20	Male
3	188	85	24.0	20	Female
4	182	70	21.1	18	Male
5	172	63	21.3	19	Female

The study was part of the evaluation of an alternative tidal volume measurement device and approved by the local ethics committee (HEC 2019/01/LR-PS). A written informed consent was collected from each subject.

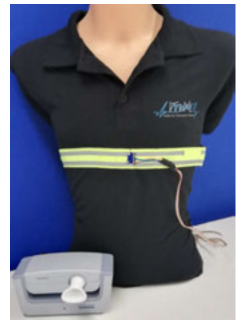

Figure 1: Prototype of the IMU-belt with ventral IMU and spirometer (reference)

2.3 Data processing

The MPU 6050 sensors have an embedded Digital Motion Processing Unit (DMP), which has pre-installed filter und calculation functions. For this study, the output of the Kalman-filtered quaternions q = [w, x, y, z] was used (*dmp.GetQuaternions* function of the DMP).

Using the data from the two IMUs, the relative angle θ between the ventral (q_r) and dorsal (q_d) quaternion of the IMUs was calculated.

$$q_r = q_v * {q_d}^{-1} \quad (1)$$

During breathing, the global angles of q_v and q_d changed in different ways, and so did the relative angle θ between them. This angle θ was calculated by:

$$\theta = 2 * arccos(|w_r|) \quad (2)$$

where: w_r is the real part of the relative quaternion q_r.

The change of the relative angle θ was used to calculate the respiratory rate and was compared to the reference respiratory rate of the spirometry measurement.

The collected data were stored on a laptop and then further processed in MATLAB. First, a Butterworth-bandpass-filter of 10^{th} order was used to filter out and to eliminate disturbances and motion artefacts of the IMU-data. A frequency range of 0.1 to 1.5 Hz was used (Figure 2) for bandpass filtering, to reduce the signal to the needed spectrum. This would lead to a respiratory rate spectrum from 6 to 90 breaths per minute. An adult typically has a breathing rate of 12-18 breaths per minute at rest. Thus, the chosen spectrum fits the normal breathing range and further above as needed for the testing.

To adjust the IMU data to the data of the spirometer, the *xcorr* function in Matlab was applied on the filtered signals. For further analysis, Fast Fourier Transformation (*fft* function in MATLAB) was utilized individually in each breathing phase to obtain the respiratory frequencies (RF) of both signals; subsequently, the results were compared.

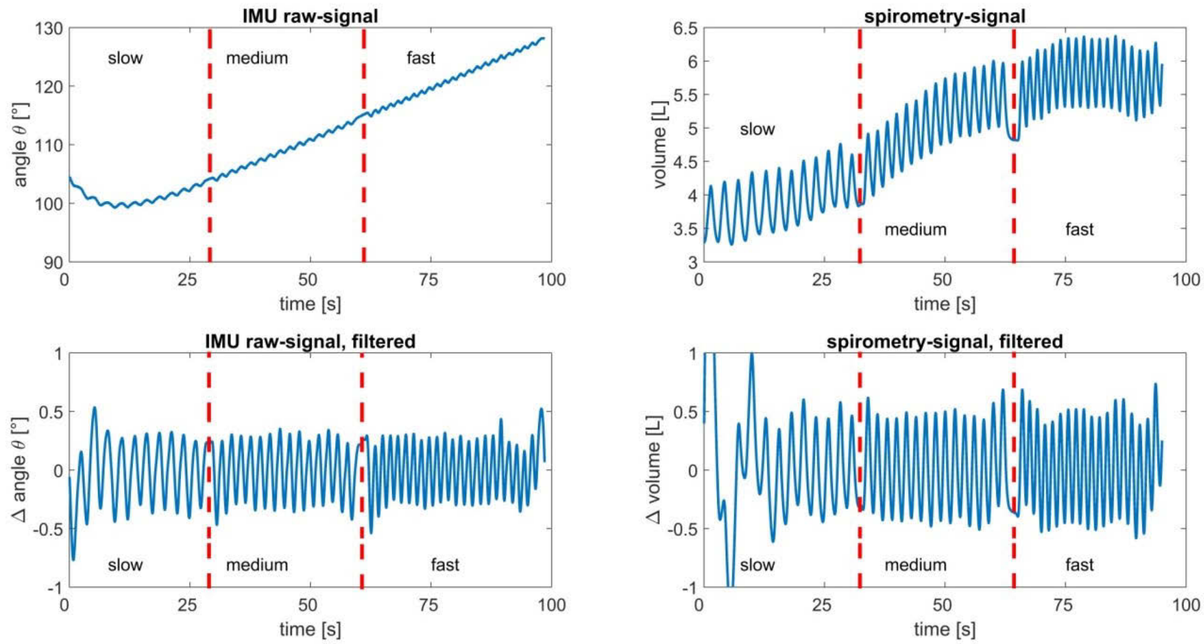

Figure 2: Signal filtering process. IMU-signal (left) and spirometry signal (right), illustrated based on the data of subject 1. (Butterworth bandpass filter 10th order, $f_{cut\text{-}off,\,lower}$ = 0.1 Hz and $f_{cut\text{-}off,upper}$ = 2 Hz).

3 Results

Figure 2 shows the obtained raw data of the IMUs and the spirometer as well as the data after bandpass filtering. FFT can separate the three different respiration frequencies (slow, medium, and fast).

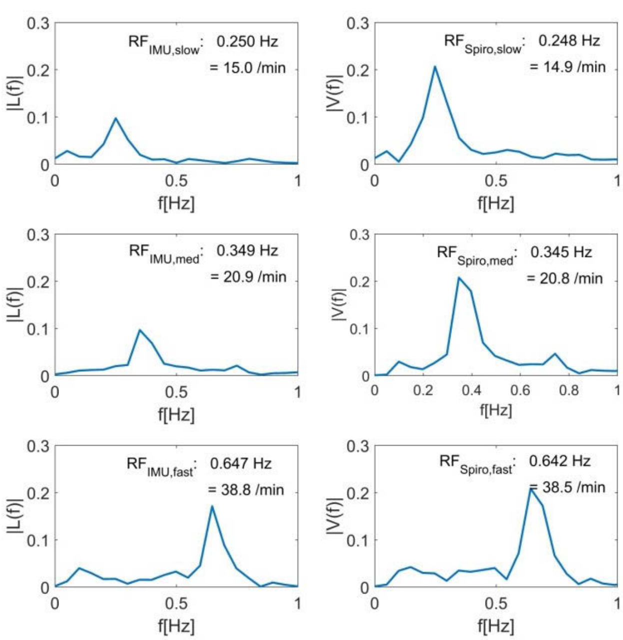

Figure 3: Frequency analysis with FFT, based on the data of subject 2.

Table 2 shows the results for respiratory rates via FFT and its deviations between the two measurement systems for the slow breathing rhythm, while Table 3 shows the results for the medium breathing rhythm and Table 4 for the fast breathing. Finally, Figure 3 illustrates the results of the FFT.

Table 2: *Respiratory rate of IMU and Spiro data (slow)*

Subject	$RF_{IMU\text{-}belt}$ [breaths/min]	$RF_{Spirometer}$ [breaths/min]	Deviation [breaths/min]
1	24.0	23.8	0.2
2	15.0	14.9	0.1
3	20.0	19.8	0.2
4	16.0	15.8	0.2
5	14.4	14.3	0.1

Table 3: *Respiratory rate of IMU and Spiro data (medium)*

Subject	$RF_{IMU\text{-}belt}$ [breaths/min]	$RF_{Spirometer}$ [breaths/min]	Deviation [breaths/min]
1	29.9	29.7	0.2
2	20.9	20.8	0.1
3	39.9	39.5	0.4
4	19.9	19.7	0.2
5	24.0	23.8	0.2

Table 4: *Respiratory rate of IMU and Spiro data (fast)*

Subject	$RF_{IMU-belt}$ [breaths/min]	$RF_{Spirometer}$ [breaths/min]	Deviation [breaths/min]
1	35.8	35.6	0.2
2	38.8	38.5	0.3
3	75.5	74.8	0.8
4	35.8	35.4	0.4
5	38.2	38.0	0.2

4 Discussion

The IMU-belt is a promising approach for respiratory rate determination. The angle between dorsal and ventral quaternion provides a respiratory rate which is in high correlation to the respiratory rate obtained by the spirometry.

This study showed that the deviation of the respiratory rates between the two measurement systems increases with higher respiratory frequency. At slower breathings rates (< 30 breaths /min) the deviation is less than 0.2 /min. Above 30 breaths per minute, the deviation tends to increase, but it is still less than 0.8 /min and allows accurate measurements.

Subject 3 had a medium respiratory rate in the range of the fast rates of the other subjects, and the fast-respiratory rate of this subject was close to the maximal spectrum of the belt. The measurement of subject 3 showed that the belt could be used even in case of breathing frequencies beyond normal breathing frequencies of everyday life. Considering, that in most cases the breathing rate of an adult is below 40 breaths per minute, except extreme sports, the accuracy of the belt in that range is high. Here, the deviation to the reference signal is less than 0.4 breaths per minute.

The bandpass filtering focused on the relevant frequencies and noise was filtered out, as well as movements of the upper body, which were not respiration induced. These movements seem to be neglected by the system, which might be a result of filtering and the usage of two IMUs. Movements like bending or twisting of the upper body seem to affect both IMUs in the same way. Thus, the resulting quaternion, respectively, the angle θ between dorsal and ventral quaternion, seems to be barely affected. However, to evaluate that, further measurements should be done involving a higher number of participants (more than 15) during exercise to analyse the robustness of the system and to allow statistical analysis of the results. Another study should be performed to evaluate these outcomes for elderly subjects and patients with lung diseases.

5 Conclusion

The introduced IMU-belt can analyse the respiratory rate accurately. Combined with ECG (electrocardiogram) measurements, the belt could be used for monitoring heart and respiratory rate and may provide a system for the surveillance of main vital parameters in clinical settings or home care.

Author Statement and Acknowledgement

Research funding: This research was partly supported by the German Federal Ministry of Education and Research (MOVE, Grant 13FH628IX6) 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 or equivalent committee.

References

[1] Miller, M.R. ; Hankinson, J. ; Brusasco, V. ; Burgos, F. ; Casaburi, R. ; Coates, A. ; Crapo, R. ; Enright, P. ; Van Der Grinten, C.P.*, et al.*: Standardisation of spirometry. In: *Eur Respir J* 26 (2005) Nr. 2, S. 319-38.

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

[3] Konno, K. ; Mead, J.: Measurement of the separate volume changes of rib cage and abdomen during breathing. In: *J Appl Physiol* 22 (1967) Nr. 3, S. 407-22.

[4] Chu, M. ; Nguyen, T. ; Pandey, V. ; Zhou, Y. ; Pham, H.N. ; Bar- Yoseph, R. ; Radom-Aizik, S. ; Jain, R. ; Cooper, D.M.*, et al.*: Respiration rate and volume measurements using wearable strain sensors. In: *NPJ Digit Med* 2 (2019) Nr. 8, S. 019-0083.

[5] Karacocuk, G. ; Höflinger, F. ; Zhang, R. ; Reindl, L.M. ; Laufer, B. ; Möller, K. ; Röell, M. ; Zdzieblik, D.: Inertial Sensor-Based Respiration Analysis. In: *IEEE Transactions on Instrumentation and Measurement* (2019), S. 1-

[6] Cesareo A, Previtali Y, Biffi E, Aliverti A. Assessment of Breathing Parameters Using an Inertial Measurement Unit (IMU)-Based System. *Sensors (Basel)*. 2018;19(1):88. Published 2018 Dec 27. doi:10.3390/s190100