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The Vehicle as a Diagnostic Space: Efficient Placement of Accelerometers for Respiration Monitoring During Driving

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Abstract. In-vehicle monitoring of bio-signals in real time is still an unsolved problem. To support continuous respiration monitoring, this work intends to reveal where such sensors can be deployed and how their signals are affected by noise during autonomous driving. A Shimmer3 IMU module was attached to the passenger seatbelt of a test vehicle for respiration monitoring. Four positions at the seatbelt (*Shoulder, Chest, Side-Waist* and *Waist*) were tested under four conditions (*Engine Off, Engine On*, and *Drive on Flat* and *Uneven Road*). The data capture protocol ensures the same respiration rate in all conditions. Three testers were measured with two repetitions each yielding a total of 96 records of 60 s lengths. All signals were low-pass filtered. Then, the fast Fourier transform was applied. We evaluated the highest peak in the frequency domain. If the highest peak in the range of 0.1 – 0.4 Hz was identified at the same position, the condition is counted as true. Surprisingly, side-waist position yields 67% on the uneven road while chest and waist (both in the middle of the subject) are unsuitable. In conclusion, monitoring respiration on the seatbelt is possible with accelerometers while driving, if the right sensor position is chosen. In future, smart textiles will be used to integrate unobtrusive and inexpensive biomonitoring in the vehicle.

Keywords. Health monitoring, respiration, accelerometer, accidental informatics

1. Introduction

In present days, a car is not just a vehicle, for many people, it is a vitally integrated part of their everyday lives. In fact, it is an important living space, where people spend a considerable amount of lifetime, typically on regular schedules. However, the use of a private vehicle may also cause severe road safety issues. Road injuries are still among the ten leading causes of death in the world [1]. To release drivers’ workload, the automotive industry has been working towards autonomous driving, and many assistant systems are in place already [2]. However, the monitoring of drivers’ health state and fitness is still an open question. It has become a key issue delivering health-relevant input to these assistance systems [3]. In addition, assisted or autonomous driving allows to convert the travel into a regular medical check-up: the vehicle is turned into a diagnostic space.

Monitoring the respiration patterns, as well as respiration rate in real-time is a critical need in diagnostics and therapeutics [4]. As respiration induces rhythmical body

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movements, measuring such movements can be used as an indirect approach for monitoring respiration. Previous research has shown that an accelerometer can be utilized as a simple, low-cost, and unobtrusive instrument for monitoring respiration movement [5]. Respiration patterns were successfully detected based on the tri-axis signals of accelerometer [6]. Besides, Martinez et al. already applied an accelerometer on the seatbelt to measure respiration, but determining the most suitable position for the accelerometer was not in their scope [7].

The two main principles for achieving user acceptance of an automated data collection system are unobtrusive deployment and ambient embedding. Following these principles implies (i) no need of an additional operation to the monitored persons (e.g., drivers and passengers), and (ii) no influences on environment and behavior (e.g., driving) [8]. However, measuring signal during driving is challenging due to the complicated and unpredictable condition. Engine operation, vehicle vibrations, and driver's non-stationarity introduce noise into the signal. A better understanding of the impact of these factors on the signal would contribute to sensor deployment, data processing, and information extraction.

In this work, we investigate the performance of an accelerometer attached to the passenger seatbelt for monitoring respiratory movement in real-time. We intend to answer whether acceleration sensors can be deployed for respiration monitoring in a moving vehicle and which position is suitable best for unobtrusive integration.

2. Methods

2.1. Experimental design

An experiment with three healthy volunteers was designed to test the performance of an accelerometer at four different positions on the seatbelt under four driving conditions. The participants are of average body size and weight. The BMI for male Tester 1 (T1) is 23.8, for male Tester 2 (T2) 23.4; and for female Tester 3 (T3) 22.0. The four positions on the seatbelt were assigned (Figure 1). To simulate autonomous driving, the testers were sitting on a passenger seat, an accelerometer was attached to the testers' seatbelt. Under the four driving conditions:

- *Engine Off* (C1): tester sat in the parked vehicle while keeping the engine off;
- *Engine On* (C2): start the engine but keep the vehicle in a parking lot;
- *Drive on Flat Road* (C3): drive the vehicle on a random street with a flat surface without potholes at a speed 20 - 30 km/h; and
- *Drive on Uneven Road* (C4): drive the vehicle on a gravel parking lot at a speed 10 ± 2 km/h.

the testers were required to perform peaceful breathing for at least one minute in the vehicle before the recording sequence was started. Each volunteer was recorded twice.

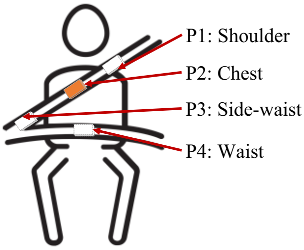

Figure 1. The four positions for attaching accelerometer on the passenger seatbelt.

2.2. Hardware

The test vehicle (Mini One, 66 kW, BMW, Munich, Germany) was operated to create the four driving conditions. To monitor respiratory movement, the sensor system (Shimmer3 IMU, Shimmer, Ireland) embedded with a three-axis accelerometer was attached to a pre-selected position on the seatbelt by stick tape. The sampling rates for the sensor was configured as 204.8 Hz. The acceleration of the tri-axis was used to reflect the respiration activity of the tester. To store the data, a laptop (Latitude 5480, Dell, Texas, USA) was carried in the vehicle. A connection between the Shimmer module and the laptop was established via Bluetooth.

2.3. Data collection

During the experiment, the data was directly transferred to the Consensys (Version v1.5.0) database running in the laptop. The experiment at each position per condition was considered a separate session. Therefore, we collected a total of 96 sessions (4 positions, 4 conditions, 3 volunteers, 2 repetitions) of 60 seconds lengths.

2.4. Data processing and analysis

We firstly transformed the signal into frequency domain using fast Fourier transform (FFT). The three-axis signals were combined into one channel by adding up the amplitudes of the FFT signal, i.e.,

$$V = |FFT(x)| + |FFT(y)| + |FFT(z)|$$

We defined a rule to evaluate the performance of V to reflect respiratory movements as *positive* or *negative*. An *evident peak* was defined as within a frequency interval $[f_0 - 2f_r, f_0 + 2f_r]$, if f_0 refers to the highest amplitude A and $0.9A > A_2$, where A_2 is the second highest amplitude in the interval, and f_r is the FFT frequency resolution. For the data of sessions at position P, we used the signal under C1 as a reference since the clear waveform reflecting the respiratory movements.

(1) Under the C1, if there is an *evident peak* within the frequency interval [0.1 Hz, 0.4 Hz] of V, the signal is *positive* for reflecting respiratory movements, the corresponding frequency of the peak is f_p.

(2) Under conditions C2, C3 or C4, if there is an *evident peak* within the frequency range $[f_p - 2f_r, f_p + 2f_r]$, where f_p refers to an evident peak under condition C1, we consider the signal is *positive* for reflecting respiratory movements.

Finally, we calculated the positive rate under each condition at each position.

3. Results

At some positions, the frequency domain can manifest evident peaks in the pre-selected range (Figure 2), while at others peaks can be hardly found (Figure 3). An amount of high-frequency noise was introduced in the signal when the engine was started. The frequency spectrum shows when the vehicle was driven on the road, more noise of low frequency is introduced (Figure 2 and Figure 3). The accelerometer performs better under the condition C2 than C1. Under the condition C3, the respiration is reliably detectable with a positive rate of 95.83% (23/24) disregarding of testers and positions (Table 1).

The results indicate that the accelerometer performs better when attached to the positions shoulder and side-waist, instead of the chest as many can imagine. P3 (*Side-Waist*) can yield 66.67% positive performance on the uneven road.

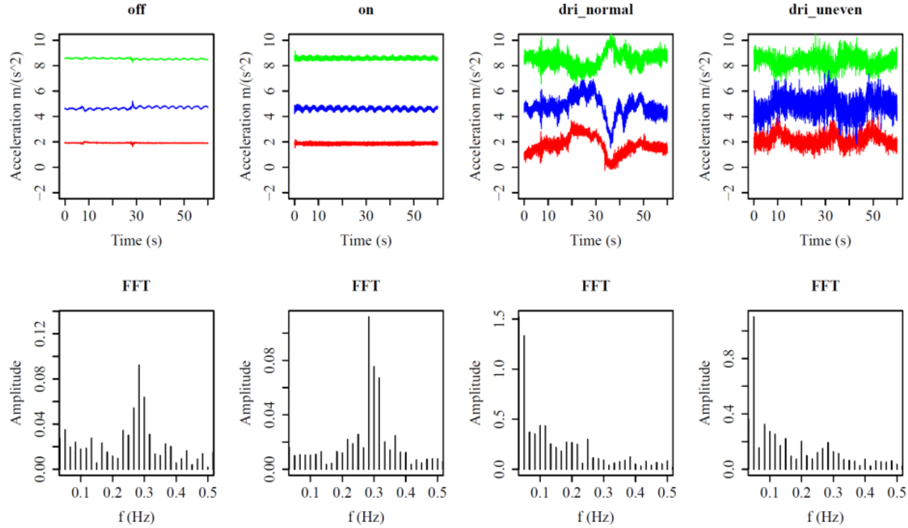

Figure 2. The raw signal at P3 (*Side-Waist*) of an experiment and the multiplied amplitude of FFTs.

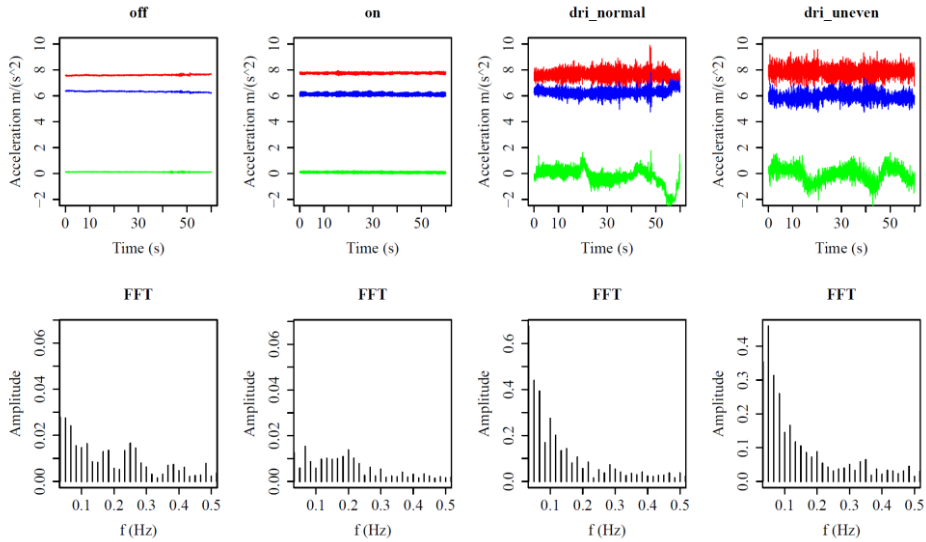

Figure 3. The raw signal at P4 (Waist) of an experiment and the multiplied amplitude of FFTs.

Table 1. The positive performance rate across conditions and positions.

Conditions	P1	P2	P3	P4	All positions
C1	100% (6/6)	66.67% (4/6)	100% (6/6)	66.67% (4/6)	83.3% (20/24)
C2	100% (6/6)	100% (6/6)	100% (6/6)	83.33% (5/6)	95.83 (23/24)
C3	50% (3/6)	33.33% (2/6)	33.33% (2/6)	33.33% (2/6)	37.5% (9/24)
C4	50% (3/6)	0 (0/6)	66.67% (4/6)	0 (0/6)	29.17% (7/24)
Sum	75% (18/24)	50% (12/24)	75% (18/24)	45.83%(11/24)	61.46% (59/96)

4. Discussion and future work

The deployed position of a sensor plays an important role in measuring evident signals. The experiment results show that the performance of an accelerometer varies strongly as for different positions under a range of conditions. In general, the accelerometer at the *Shoulder* and *Side-Waist* positions on the seatbelt provides the best results for monitoring respiration. The underlying reason could be due to the higher tension on the fixed end. Our findings can facilitate the manufactures implementing textile accelerometers in the seatbelt. The P3 can generate 66.67% positive rate on the uneven road without any sophisticated signal analysis, implying the possibility to estimate respiration rate by inexpensive acceleration sensors under real traffic conditions.

A moving vehicle is a dynamic environment, which makes the collection of accurate data a challenging task. When the engine is started, a variety of noise is introduced to the signal. The data processing rule considered the individual difference in that each individual has her/his own respiration rhythm. The data processing could serve as an inspiration for calibration in signal processing. The experiment could be carried out with a second accelerometer, by which the recorded noise of the second accelerometer can be extracted from the data of the other sensor. This would also facilitate the filtering of the data and improve signal processing.

Human-vehicle interaction is changing through autonomous driving. During driving multiple objects need to be operated to guide the vehicle to run appropriately, which provide many opportunities to collect data through these interactions. By analyzing the existing driver-vehicle interaction model, we believe that a sensor-enhanced vehicle should keep up with the features of future vehicle design. While the steering wheel and the gear stick might not be necessary for future models, the seat system would continue to be an essential part. In future, a variety of sensors should be considered for multiple purposes turning the vehicle into a diagnostic space.

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