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Mobile wearable device for long term monitoring of vital signs

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ABSTRACT

In long-term prevention and in rehabilitation of health of elderly people the recording of vital signs plays an important role. Especially the progress of rehabilitation can be deduced from the recording of an electrocardigram (ECG), blood pressure and body temperature. In this paper we present a wireless coupled recording device for long-term monitoring of these vital sign signals. We record the ECG, the blood pressure and the skin temperature and include a 3D-acceleration sensor for the determination of the movements during recording. To deal with motion artifacts in all recorded properties we use data fusion to reject or correct distorted vital sign signals.

1. Introduction

The procedures and employed instruments to supervise stationary rehabilitation are well established. Especially in the case of elderly people the main advantage of stationary rehabilitation is to assure a high compliance of the necessary training. For instance in ergometer training stationary instruments can be used with almost no motion artifacts. Data evaluation can be accomplished by sophisticated software and human supervision ensures medical assistance if necessary. The disadvantages of stationary rehabilitation are the necessity for the patient to visit a clinic or training center, the access is only possible by appointment, generally during the week. Only small groups of patients can be trained simultaneously. The human medical assistance together with the training equipment and costs for buildings and maintenance contribute to the high costs of rehabilitation. Therefore, we investigate the possibility of mobile rehabilitation [1] with automated mobile supervision, which can be an alternative for many patients.

In mobile rehabilitation for example of heart disease or chronic obstructive pulmonary disease (COPD) patients the long-term recording of vital signs is desirable, in excess of the well established long-term ECG and blood pressure recordings. The addition of further sensors with more electronics will generally increase the energy requirements and thus the cost of operation. A costly and complicated recording device will have a low compliance. Therefore, a long battery life, wireless communication and maintenance free operation are prerequisites for a new device with high compliance. Such a mobile device can only be used in rehabilitation if low error vital sign recordings [2] and – for automated supervision – reliable alarm signals can be generated. To deal with motion artifacts a time synchronous recording combined with data fusion of the contributing sensors should be realized.

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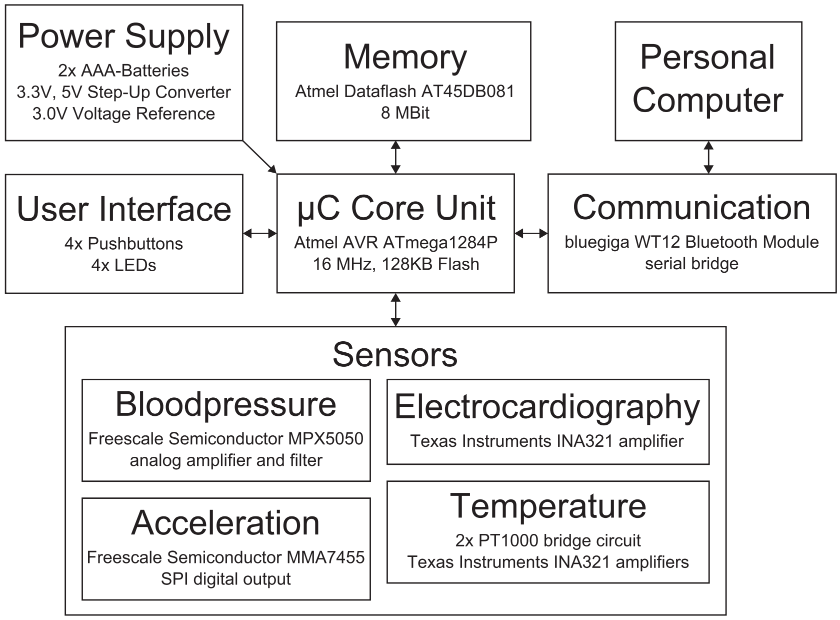

Fig. 1 – Block diagram, vital sign watch.

2. Related work

The field of wearable vital sign monitoring has been examined in several similar projects and reviews [3–7]. In addition to configurable platforms for various kinds of sensors (ShimmerTM [8], NeXus-10 [9]) there are approaches for clothing with integrated sensors [10]. Our device is most likely comparable to the AMON project [11] which also covers the development of a wrist worn multi-sensor device. In difference to AMON, our goal, besides the recording of ECG, bloodpressure, blood oxygen saturation, movement and temperature, is the development of algorithms which perform a data fusion of long term recorded values gaining more precise information about the vital status. Evaluation of sensor data, which could be overlayed by motion artifacts, would also be possible with data fusion. Furthermore, minimizing the energy requirements will be aimed for long battery lifetime which will increase the compliance especially for elderly people (e.g. those with limited fine motor skills).

3. System setup

In our device we include a one-channel ECG together with the blood pressure measurement and body temperature determination. In the following sections we shortly describe the sensor and hardware setup in our device. The whole recording device is operated under control of the microcontroller Atmel ATmega128P. In Fig. 1 the block diagram and in Fig. 2 a photo of the prototype is shown.

3.1. *Electrocardiography*

The ECG is determined from the electrical potential difference between two electrodes (single use) in galvanic contact to the skin, as commonly used to record the ECG. The difference of both channels is determined by an instrumentation amplifier Texas Instruments INA321. This signal is digitized by the internal 10 bit AD-converter of the microcontroller. From the one-channel ECG in comparison to the blood pressure measurement the heart rate and the heart rate variability can be deduced. Also, extra systoles can be detected.

3.2. *Blood pressure*

As described in literature [12–14] the blood pressure is determined by measuring the oscillations in an inflatable handcuff. After filling the cuff with ambient air by a compressor it will slowly be deflated producing a characteristic pattern of peak amplitudes. The mean cuff pressure with the highest amplitude signal equals the mean arterial pressure (MAP). With two different thresholds before and after the occurrence of MAP it is possible to identify systolic and diastolic blood pressures of the subject. The electrical signal from the pressure transducer is split up into two different paths where it is amplified and filtered. The algorithm requires two data sets for the calculations. The first set contains the low-pass filtered recorded mean cuff pressure values, the second one is the high-pass

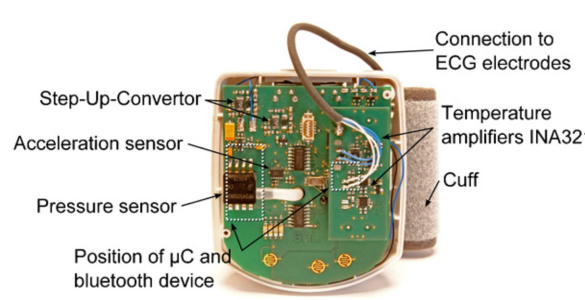

Fig. 2 – Top view, prototype PCB, vital sign watch.

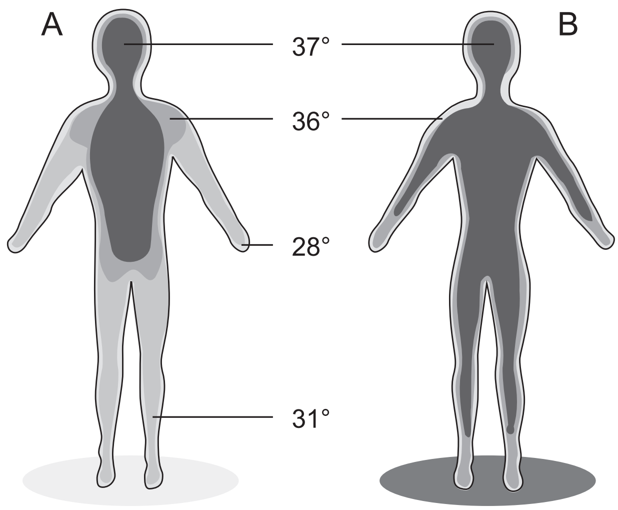

Fig. 3 – Core temperature distribution in (A) cold and (B) warm environment after [15].

filtered and amplified oscillation data. After analog preprocessing, the signal is sampled by two ADC channels. Since the mean cuff pressure does not change as quickly as the oscillating signal, the required sample rate can be much lower. Recording of raw pressure sensor data is required since it will be used to perform additional calculations.

3.3. *Body temperature*

The body temperature of relevance is the core temperature within the body. At the wrist only a more or less reduced temperature can be measured which depends on the environment (Fig. 3) and the subject itself (Fig. 4). Changing the ambient temperature (e.g. performing a cold shower) causes a major drop at the wrist temperature (compare Fig. 5). After a few minutes, the wrist temperature reaches the previous measured offset of about 3 degrees in a resting state. We use a second sensor to read the ambient air temperature. By means of the difference between both values and the subject specific offset value which has to be calibrated individually it is possible to get a corrected temperature of the body and additionally the heat flow at the wrist.

3.4. *Acceleration sensor*

The measurement setup includes a Freescale MMA7455, a 3-axis digital 10 bit accelerometer directly placed in the mobile recording device. With the sensor it is possible to determine the hand and arm movements. Due to the influence of the terrestrial gravitation in the sensor data, the absolute orientation of the device and therefore the orientation of the subjects arm can be detected additionally.

Table 1 – Sampling frequencies and resulting data rates for the sensor data transmission.

Sensor	Sampling frequency	Byte per second
ECG	1 kHz	5 kB/s
Blood pressure 1	1 kHz	5 kB/s
Blood pressure 2	100 Hz	0.5 kB/s
Body temperature	0.1 Hz	0.5 B/s
Ambient temperature	0.1 Hz	0.5 B/s
Acceleration X	200 Hz	1 kB/s
Acceleration Y	200 Hz	1 kB/s
Acceleration Z	200 Hz	1 kB/s
Control overhead	–	$\leq$ 0.05 kB/s
Sum data rate	–	13.55 kB/s

3.5. *User interface of the mobile recording device*

Using the buttons, the user can control the recording software, so it is possible to start and stop measurements or set markers without any help of another person. The vital sign watch will have a display where the user can read the familiar values for heart rate, breath frequency, blood pressure, temperature and also the daytime. The display will also be used to give instructions for the user, e.g. while a sensitive measurement is in progress and the user should take a resting position.

3.6. *Wireless data transmission*

For the data transmission we use a WT12 Bluetooth Class 2 Module from Bluegiga. A Class 2 device is specified for a link range of about 30 m line-of-sight and will work safely inside of a small apartment. Our prototype uses the Serial Port Profile (SPP) which emulates a simple RS-232 connection to the stationary computer. The SPP of the WT12 module works stable if a maximum data rate of 50 kB/s is not exceeded and therefore enough resources for our raw data transfer are provided. Table 1 lists the current sensor data rates. As described earlier in Section 3.2, the blood pressure sensor generates two sets of data and therefore requires two ADC channels with different sampling frequencies. Since the control overhead does not occur regularly (it also includes button signaling or battery voltage warnings), we only provide an estimated value for the data rate and no fixed sampling frequency.

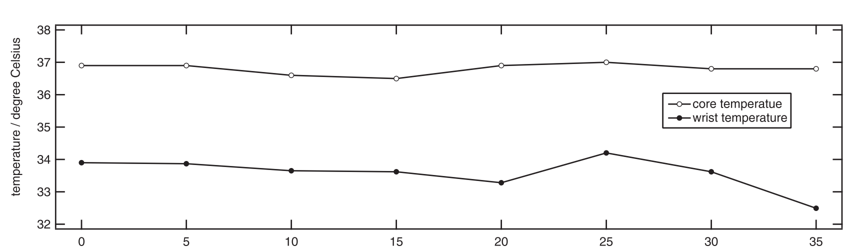

Fig. 4 – Difference between core and wrist temperature on a specific subject.

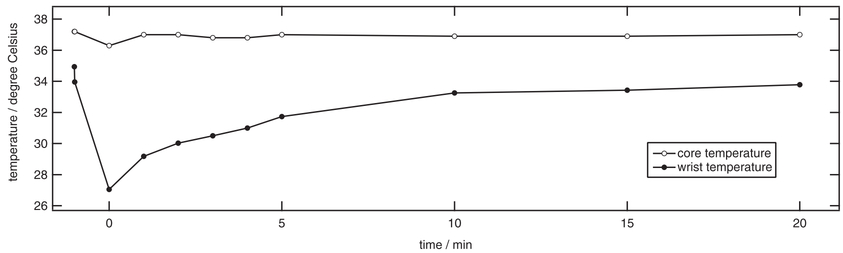

Fig. 5 – Temperature difference after cold shower.

3.7. *Energy consumption and battery runtime*

For battery operated devices it is very important to reduce the energy consumption to a minimum. Generally this is because of the increasing maintenance costs for battery exchange. With the vital sign watch we are following yet another approach: it is unacceptable for elderly people to replace a small set of batteries every day and since the devices should be worn by these people it is one of its main goals to reduce energy consumption for an especially long battery life. If the device transfers lots of raw data to the stationary computer, an increased amount of energy is required. Table 2 shows the current requirements for several components of the mobile recording device. Some require much energy for a battery operated device. If we are assuming that the oscillometric blood pressure measurement will be accomplished every 10 min using compressor, valve, bluetooth transmission and microcontroller, the power requirement of approximately 35 mA/h could be calculated. With AAA batteries with a nominal capacity of 1000 mA/h the achievable runtime would not be longer than one day. We present our approaches to reduce these requirements.

3.7.1. *Compressor and magnetic valve*

A serious problem in energy consumption is the miniature compressor and the magnetic valve. Using the cuff to detect the arrival of the pulse wave drains the battery quickly. As described earlier, it could be possible to employ the photoplethysmography method to determine the arrival time and therefore operation of compressor and valve is only required for calibration and not continuously. Supplying the LEDs in the finger clip only takes a fractional amount of the compressors and valves power.

3.7.2. *Wireless data transmission*

The chosen bluetooth interface requires 100 mA at the utmost. Using a proprietary solution would allow us to low-level control the interface and switch it off every time no transmission is required. This solution will reduce the maximum power requirements for the wireless interface to 20 mA. By the use of error detection and correction, only high quality data have to be transmitted. Additionally, a special transmission protocol reduces control overhead.

Table 2 – Current requirements, active mode.

Component	Required current
Cuff compressor	300 mA
Magnetic valve	150 mA
ECG/photoplethysmography	$\leq$ 20 mA
Bluetooth interface	100 mA
Microcontroller (16 MHz, 5 V)	10 mA

3.7.3. *Microcontroller*

To provide enough processing power, the microcontroller is clocked at 16 MHz. In case the full speed is not required, the controller could be operated at a lower clock frequency where it also requires less supplying voltage than 5 V. Since the microcontroller is the only part in the prototype which runs at 5 V, this also allows omitting a step-up boost converter and a logic-level shifting device which also reduces energy consumption and size of the printed circuit board. Running the same microcontroller at 4 MHz with a voltage supply of only 3 V, its power consumption reduces to 1.5 mA.

4. Sensor fusion for error detection

The fusion of data from different sources unveils special important informations, as the occurrence of extra systoles from the comparison of ECG and blood pressure signal. Pulse watches combine heart frequency with the information about age and gender to determine the energy expenditure in physical activity during sports [16]. Additionally, also error detection and error correction can be accomplished by fusion of time synchronous data. Therefore, we employ a common time base for the recording of all sensor data. From this time base we also derive the daytime and date to use the device as watch, the so-called vital sign watch. The data are transferred wireless by the Bluetooth protocol to a personal computer. If the connection is interrupted, the data could be stored on internal flash memory in the mobile recording device. Possibilities for data fusion of the different sensors are collected in Table 3.

4.1. *Fusion of ECG and blood pressure signal*

Analyzing the ECG signal only, it is possible to determine the heart rate and – while the subject is in a resting state – the breath frequency as evaluated from the heart rate variability in ECG [17] (Fig. 6). The resting state is determined by the data from the acceleration sensor. Furthermore, the heart rate variability, analyzing the RR time intervals within a Lorenz Plot, can be an indication for a heart disease as advanced congestive heart failure [18–20].

Table 3 – Possibilities for sensor data fusion.

	Vital signs		
Fusion data	Electrocardiogram	Bloodpressure	Wrist temperature
Ambient temperature	Energy expenditure	Energy exp.	Body temperature Heatflow
Acceleration data	Physical activity Artifact detection	Energy exp. Artifact det.	Energy exp.
Electrocardiogram	–	Extra systoles Breath frequency Pulse transition time Artifact det.	Energy exp.
Body temp. (derived)	Energy exp.	Energy exp.	–

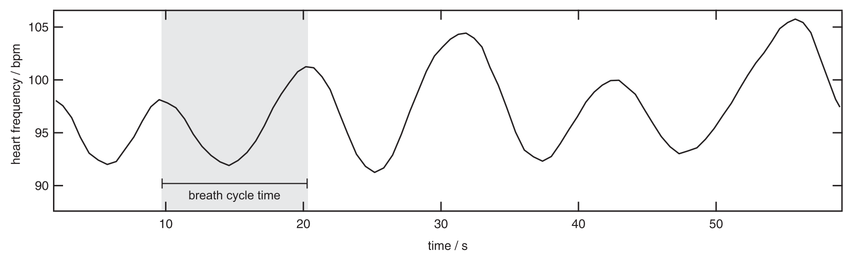

Fig. 6 – Heart rate variability and breath frequency determination.

Comparing the ECG and the pressure sensor signal, we get two successive peaks. The first peak occurs at the ECG sensor and shows the R wave of the QRS complex indicating the heart muscle activation and start of a pulse wave through the body. After a time between 200 and 300 ms this pulse wave arrives at the handcuff, generating a second peak at the pressure sensor (Fig. 7) or in a possible blood oxygen saturation sensor. The measured pulse transition time can be used to calculate a beat-per-beat blood pressure as described [21,22]. Additionally, knowing the occurrence of the R wave and the mean pulse transition time we can predict a time window for the pulse wave from the pressure sensor to arrive. Other peaks will be marked as motion artifacts and can be ignored.

4.2. *Fusion of blood pressure and body temperature*

An increased skin temperature usually indicates a higher blood flow through the extremities. Combined with the measurement of a higher blood pressure and heart rate we conclude increased energy expenditure in physical activity. To eliminate false detections, we are using the acceleration sensor to monitor the subject's activity. The heat flow between the body surface and ambiance is determined from the measured temperature difference of two temperature sensors, one in contact to the skin and the other measuring the ambient temperature. When thermally isolated (clothing and blanket) it is possible to detect a subject's fever by measuring high

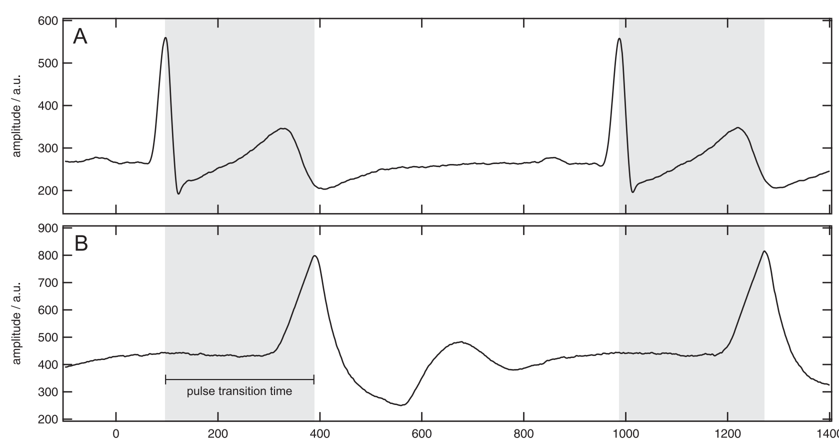

Fig. 7 – (A) Two R-waves of an ECG signal. (B) Pressure changes in the devices wrist-cuff. The shaded area illustrates the duration of the pulse transition. The time measurement starts at the easily detectable R-wave peak in the ECG signal and stops at the successive peak in the pressure sensor signal.

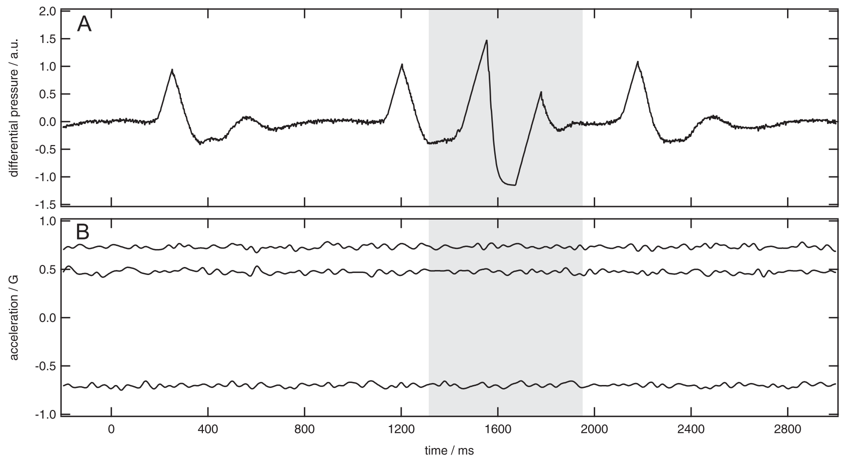

Fig. 8 – (A) Motion artifact at the pressure sensor caused by finger movement. (B) Simultaneously recorded acceleration sensor data shows no significant changes.

temperatures at the skin. The detection of hypothermia could also be possible.

4.3. *Fusion of acceleration data and ECG*

By analyzing the 3D-acceleration sensor data it is possible to perform a fall detection of the wearer [3]. Especially for elderly people falls are dangerous because it takes a long time to recover. In special cases, the automatic detection of a fall could be lifesaving when there is no assistance to call an ambulance. Falls or the increased tendency for falls could be determined from long-term recording of these acceleration data [23,24]. Combining the accelerometer with ECG we can distinguish the sleep state (reduced motion, low heart rate, lying position) or state of physical activity (higher heart rate and upright position). Since the ECG is currently recorded from electrodes with galvanic contact to the chest the ECG is not very sensitive to motion artifacts, and therefore can be evaluated for physical activity monitoring.

4.4. *Motion artifacts*

The cuff pressure sensor is very sensible to motion artifacts due to the high amplification of its output voltage which is required to record the oscillations. While the arm or hand of the wearer is performing any kind of actions it is not possible to read the blood pressure reliably using the mentioned oscillation method. A workaround would be the calibration of the pulse transition time method during a resting state. Once calibrated, we can get the blood pressure only from the transition

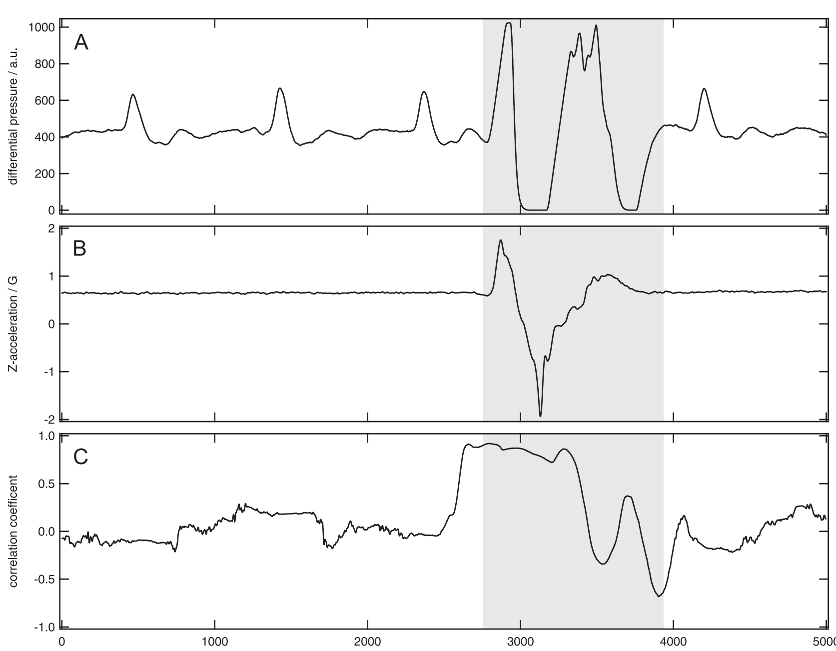

Fig. 9 – (A) Motion artifact at the pressure sensor caused by movement of the whole arm. (B) Simultaneously recorded acceleration in Z-direction. (C) Moving correlation coefficient between A and B calculated through a 1000 values window.

time. It's less affected by motion artifacts because we get the relevant information from the pulse occurrence and not from the pulse amplitude. Artifacts within the ECG signal or body temperature could be rejected from the detected motions if the difference between the average value and the new measured value is too high. Generally, it's possible to use detected motions by the accelerometer as noise cancelling [25,26] or at least for evaluation of the sensor data validity [27]. Special care has to be taken for the position of the accelerometer within the mobile recording device, since eventually finger movements deteriorate the pressure signal but are not detected by the accelerometer, as depicted in Fig. 8. As an example, the figure shows the trace of the recorded pressure sensor data. The motion artifact detected in the shaded area is caused by the movement of the index finger. Although there is no detectable movement at the acceleration sensors (B), the detection is still possible because the peak occurs at the wrong time window compared to the surrounding peaks. The time window for the next pulse can be calculated from measuring the prior pulse transition times. Due to no detected motions, significant changes in blood pressure respective pulse transition time are not expected and the peak which does not occur within the window could be blanked out. In this case no information gets lost. Fig. 9 shows another artifact caused by a single motion of the arm. This time, the relevant peak signal at the pressure sensor is overlaid by the artifact but it can also be detected because of the accelerometer data (B) or through the correlation (C) of both sensor data.

5. Discussion

We have built a prototype using parts of the case from a commercial blood pressure monitor for the wrist (Fig. 2). All necessary sensors are placed inside (acceleration and pressure) or at the outside (temperature) of the case except for the ECG electrodes which are placed at the chest and are connected by cables. The device is powered by two AAA batteries and has four pushbuttons for user control. It currently transmits every sample of the sensor raw data wirelessly to the stationary computer where the data will be stored and processed with a common time base. Our prototype only collects and forwards the data and does not perform any calculations for data compression or analysis yet.

5.1. *Limits for error correction*

There are limits for the data acquisition in our sensor setup whose cause will be discussed in the following.

5.1.1. *Pressure sensor*

To detect the pressure changes caused by blood flow through the vessels underneath the cuff, high gain for the analog signal is required. Pressure changes caused by motion are much larger, therefore the analog signal reaches the dynamic range of the amplifier and data at the digital side get lost. Without the complete raw data, only error detection is possible but no data fusion. Fig. 9, part (A), shows the distorted pressure signal caused by arm movement. Clipping occurs at the maximum and minimum pressure peaks. Generally, movements, in this case arm or hand movements, are not easy to handle because they occur in many more degrees of freedom than a single 3D acceleration sensor can record.

5.1.2. *Temperature measurement*

Extreme ambient temperatures are out of range for compensation calculations from the skin temperature at the wrist to the core temperature of the body. Also quickly changing ambient temperatures will deteriorate the compensation because the temperature distribution in the body needs time to adjust.

6. Conclusions

In conclusion, we describe the requirements for mobile supervision of vital signs in rehabilitation. The simplicity of operation of the recording device is especially well suited for high compliance by elderly people. We employ data fusion of the various vital sign signals to both reduce the error rate and deduce further meaningful measures for the determination of the health state of the wearer.

With in the discussed limitations, it is possible to introduce a device with low power consumption and high compliance which is suitable for long time monitoring of vital data. The device itself should perform basic data processing to reduce the energy for raw data transfer. Further complex calculations could be performed by a stationary computer.

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