EVALUATION SYSTEM FOR MONITORING OF VITAL PARAMETERS AND ACTIVE BODY CLIMATE CONTROL

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Abstract: This work presents a textile integrated evaluation system for active body climate control. The evaluation system registers several vital parameters of the user (skin temperature, skin relative humidity, heart rate, breathing rate and 3D acceleration data), its current subjective feedback and some surrounding parameters (temperature and relative humidity) and thus automatically controls the air ventilation level inside a cooling vest. For the climate control, a regulation algorithm influencing the body heat exchange processes and leading to thermal comfort at different workloads and different surrounding conditions is heuristically designed. In addition, a field study is conducted. This study involves 11 test persons and aims at validating the sensor data of the evaluation system and determining the energy expenditure of the body from the sensor data by analyzing the correlation between these data and the reference data of a spirometer. Besides, a verification of the suitability of the evaluation system for daily use and a validation of the implemented regulation algorithm is conducted.

1 INTRODUCTION

The active body climate control has several interesting aspects and its benefits can be shown in different use case scenarios. In fact, it can be integrated into the protective clothing of rescue and relief personnel (fire fighters and special police units) who work under extreme thermal conditions due to the thermal isolation of their clothing, which is caused by its protective functionality (e.g. ballistic protection). In this case, the active body climate control system is primarily a cooling system that prevents overheating of the body and protects the wearing subject thereby increasing his physical performance. Another very interesting application field for such a technology is the medical field, where it can actively support the physiological thermoregulation mechanisms of elderly and weak-hearted patients and thus avoid a collapse of their cardiovascular system due to excessive heat of the surroundings.

Besides, the active body climate control offers a big potential for energy saving. In fact, a portable cooling system would need an electrical power of about 3 to 4 watts (primarily for the integrated ventilator), which corresponds to about 1/1000 of the energy consumed by a commercial room air conditioner.

Apart from compensating high surrounding temperatures, the active body climate control helps the wearing subject to transport away the generated body heat due to metabolic activity (especially through evaporation and convection). This leads to an increase of the performance even during high physical activity and contributes to a better thermal comfort.

2 METHODS

2.1 Evaluation System

In this section, the implemented evaluation System, which is used in the field study conducted to validate the reliability of the sensor data and the conceived body climate regulation algorithm, is described.

The evaluation system comprises a modular hardware set-up, which has a variety of sensors integrated into a sensor shirt, a cooling vest for the air ventilation, a control board for data processing (sensor data as well as user feedback data), regulation algorithm and wireless communication

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a) b)

Figure 1: Evaluation system: a) Sensor shirt, b) Whole system.

and a feedback interface including a scroll wheel and a PDA.

2.1.1 Sensor Shirt

In order to get an idea about the actual body climate and its energy expenditure due to physical activity, several sensors for the measurement of the vital parameters need to be used. Due to comfort and reliability issues, the sensors have been integrated into a shirt having elastic material permeable to the moisture, which better fits the body form and lets the generated evaporation heat of the body diffuse into the ventilation air. In this way the sensors do not need to be attached to the body surface and thus makes the use of the system in the field study very practical. The sensors integrated in the shirt are in addition connected to the control board by means of a detachable connector interface.

The sensor shirt includes the following vital parameter sensors:

Temperature and Moisture Sensors:

The skin temperature at the thermal balance of the body is influenced by many factors like the clothing and the metabolism or activity level of the body. Thus, its deviation from a set point temperature Tsk_{m0} can be used to recognize a ventilation need. Due to the non uniform distribution of the skin temperature (Olesen, 1973) (Crawshaw, 1975) (Fiala, 1999), this latter is measured at four positions on the body skin surface. Two digital temperature sensors are integrated in the textile area at the abdomen and the upper back. Additional two combined sensors for measuring temperature and relative humidity (temperature compensated) are used in the area of the chest and the lower back. The four temperature values are then weighted with the corresponding skin area and thus the mean skin temperature can be determined. The relative humidity at the skin surface is in addition a good index for determining the amount of energy losses in form of evaporation. This represents the biggest part of the whole energy given up to the surroundings and especially at high surrounding temperature and/or metabolic activity.

Heart Rate Sensor:

It comprises two textile electrodes integrated into the shirt and connected to an analog frontend module, which detects the QRS complexes out of the ECG signal and generates digital square pulses at each QRS event. This digital signal is connected to an input capture module of the microcontroller on the control board, where the heart rate can be calculated.

In order to improve the quality of the detected ECG signal, the cross over resistance between the skin surface and the electrodes has to be very low. In the case of sport activity the fast formation of a sweat film under the electrodes decreases the crossover resistance. In the conducted measurements a cream for ECG electrodes is applied in order to get the best signal quality.

Respiration Sensor:

It comprises a piezoelectric crystal, which is stretched by means of a band attached to the shirt at the chest level. The output signal of the sensor is proportional to tensile stress and therefore shows a good correlation with the chest movements due to the respiration.

Acceleration Sensor:

A 3D acceleration sensor is attached to the shirt in the left shoulder. Out of the three acceleration values in the three axes, the activity level can be determined (Jatobá, 2007).

2.1.2 Cooling Vest

The cooling vest is worn over the sensor shirt and integrates a space holder material, through which fresh air can circulate. The inner textile separation layer is, unlike the outer one, permeable to the moisture. The cooling vest has an air inlet at the most lower part on the back and an air outlet in the front at the most lower part of the vest. A ventilator is placed at the outlet and is responsible for the ventilation of the body by aspiring the air, which circulates from the inlet over the back, the shoulders, the chest and the abdomen towards the outlet. At the outlet the air blown out gets warmer and more humid due to the body heat, which is released especially by evaporation and convection. In addition the cooling vest integrates two combined sensors for measuring temperature and relative humidity at both the inlet and the outlet, which can be used to monitor the surrounding conditions (from the sensor at the inlet) and the thermal exchange between the body surface under the vest and the circulating air in the vest (from the sensor at the outlet). It also has a rechargeable battery, which allows up to more than 10 hours operating time of the ventilator at full performance. The applied voltage to the ventilator is controlled by a PWM modulator on the control board and thus the ventilation level in the vest can be changed according to the current level of the regulation algorithm.

2.1.3 Control Board

It is the main part of the system, where the signal processing, the climate regulation algorithm and the control of the ventilation take place. The main microcontroller of the control board PIC24FJ256GB also uses an integrated SDHC memory card in order to save all sensor and regulation algorithm data, which can be offline analyzed on a PC.

2.1.4 Feedback Interface

On the one hand, the user has the possibility to change the ventilation level according to his individual preferences through manipulating a scroll wheel, which is integrated in a wrist-band. This latter also integrates an RGB led, which is used to show the status of the system. On the other hand, the evaluation system has another interface channel namely a PDA, which communicates with the control board via Bluetooth and online visualizes all vital and system parameters.

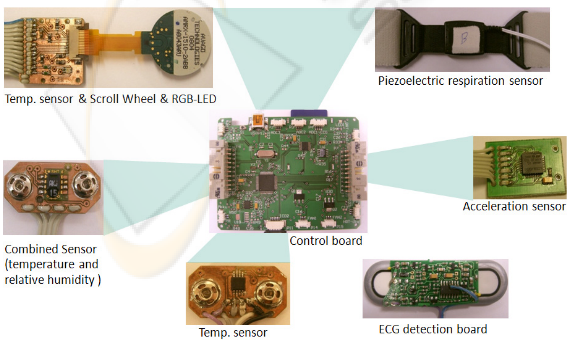


Figure 2: Evaluation system: sensor nodes and control board (in the middle).

2.2 Climate Regulation Algorithm

In order to maximize the climate comfort for the wearing subject of the evaluation system, a regulation algorithm for active body climate control needs to be designed. Outgoing from the measured and surrounding parameters, the regulation algorithm should control an appropriate actuating variable responsible of the climate control. In the designed system only the active cooling is integrated. Nevertheless, an active heating component is planned to be integrated in the next generation of the system.

2.2.1 Actuating Variable

The actuating variable for the active climate control is the ventilation level. This latter corresponds to the rotation speed of the ventilator at the outlet. This speed is controlled by the control board that varies the operating voltage of the ventilator through a PWM modulator. The voltage interval, in which the ventilator is active, is linearly split in 10 discrete levels. Since the ventilator needs a minimum voltage in order to overcome its inertia, the voltage interval taken into consideration varies from around 5.8V to 12V. In this way we get the following ventilation levels:

- Level 0 = ventilator is inactive
- Level 1-9 = ventilator is active
- Level 10 = maximal ventilation

The calculated ventilation level ($Vent_{Level}$) comprises two components: the ventilation level calculated out of the measured sensor data (Alg_{Level}) and the user level ($User_{Level}$), which is set up by the user through manipulating the scroll wheel at the wrist-band and which gives him the possibility to fine tune the ventilation level according to its individual comfort feeling and even switch it off if desired. Thereby the following formula and constraints are always valid.

$$\begin{aligned} Vent_{Level} &= Alg_{Level} + User_{Level} \\ \text{with} \quad 0 &\le Vent_{Level} \le 10 \\ 0 &\le Alg_{Level} \le 10 \\ -Alg_{Level} &\le User_{Level} \le 10 \end{aligned} \tag{1}$$

2.2.2 Regulation Algorithm

The aim of the evaluation system is to actively influence the physiological body thermoregulation as shown in figure 3.

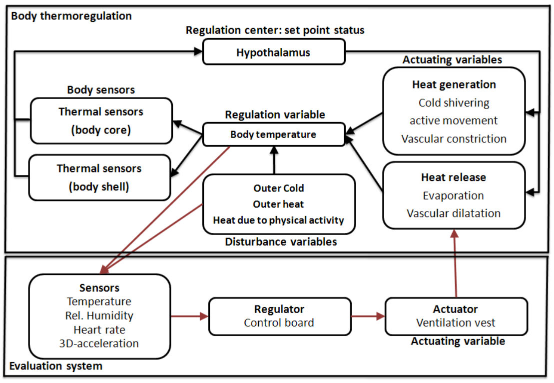


Figure 3: Active influence of the evaluation system on the body thermoregulation.

In fact, the actuator component of the implemented evaluation system supports the heat exchange mechanisms of the body by improving the evaporation and the convection. As input for the regulator, several vital and environmental parameters are measured and post processed in order to get information about the cooling needs of the user.

In a first stage, the regulation algorithm influencing the body heat exchange processes was heuristically designed. The reason behind it was that there have been neither enough sensor data nor literature sources, which exactly describe the influence of a similar concept for active climate control on the thermal processes of the body. In addition we had no reference sensor data (like spirometer for detecting energy expenditure (Hollmann, 2006)) before the field study, which reflect the quality and reliability of the sensor data and help to determine an analytical regulation algorithm. During the design phase, a load test, similar to the test in the planned field study, was conducted. In that phase, the wearing subjects had the possibility to manually set up the ventilation level by the scroll wheel according to their individual preferences. In this way, a sensor data set correlating with subjective optimum could be registered. Outgoing from the analyzed data of the temperature, moisture, heart rate and acceleration sensors the corresponding proportions for the ventilation level (respectively Tsk_{Level}, RH_{Level}, HR_{Level} and ACC_{Level}) were empirically defined. The sum of these values builds up the ventilation level out of the regulation algorithm (Alg_{Level}).

$$Alg_{Level} = Tsk_{Level} + RH_{Level} + HR_{Level} + ACC_{Level} \qquad (2)$$

In addition, the determined ventilation level of each sensor has been limited to a predefined similar range. This should minimize errors due to malfunction of the sensors during the load test.

In the following section, the different terms of formula (2) should be depicted.

The ventilation level outof the measured mean skin temperature Tsk_m is determined by formula (3) and its deviation from the set point temperature Tsk_{m0} is proportional to the thermal heat losses at the skin and thus the linear correlation with the ventilation level.

$$Tsk_{Level} = b_T \cdot (Tsk_m - Tsk_{m0}) \qquad (3)$$

with $-1 \leq Tsk_{Level} \leq 3$, $b_T = 2$ and $Tsk_{m0} = 32$ °C

Analog to the mean skin temperature, the mean skin relative humidity RH_m is calculated out of the two moisture sensors and the deviation to the relative humidity at the inlet of the cooling vest RH_{in}, corresponding to the relative humidity of the surrounding air, is normalized and the specific ventilation level can be determined according to the formula 4.

$$RH_{Level} = b_{RH} \cdot (RH_m - RH_{in}) / (100\% - RH_{in}) \qquad (4)$$

with $0 \leq RH_{Level} \leq 3$ and $b_{RH} = 3$

The heart rate correlates with the actual psycho physical load on the body and has a linear dependency with the workload (Hollmann, 2006).

$$HR_{Level} = b_{HR} \cdot (HR_{m20} - HR_0) \qquad (5)$$

with $0 \leq HR_{Level} \leq 4$, $b_{HR} = 1/29$ and $HR_0 = 75$

Thereby HR_0 designates the heart rate at rest and HR_{m20} represents the post processed heart rate signal, which results from filtering the raw signal by a non linear median filter having the width of 11, and averaging over a moving window of 20 values.

The ventilation level ACC_{Level} gained out the data of the acceleration sensor is calculated by the following formula.

$$ACC_{Level} = b_{Eeac} \cdot \mathrm{Max}\{Var\_Eeac_{m30}, Var\_Eeac_{m150}\}$$

$$\text{with } 0 \leq ACC_{Level} \leq 3,\ b_{Eeac} = 50,\ Var\_Eeac = (Eeac - 1)^2 \ \& \ Eeac = \frac{1}{f_s}\sum_{i=1}^{f_s}\sqrt{a_{xi}^2 + a_{yi}^2 + a_{zi}^2},\ f_s = 20 \text{ Hz} \qquad (6)$$

In this case the variance of the parameter Eeac, which is an equivalent for the acceleration energy, is calculated out of the energy of the acceleration signal in the three axes of the ACC sensor (Jatobá, 2007). $Eeac_{m30}$ and $Eeac_{m150}$ represent the post processed Eeac values, which are averaged over a moving window of respectively the width of 30 and 150 values. The $Eeac_{m150}$ enables the integration of a relaxation phase of 3 to 5 minutes depending on the activity time and intensity, which precede a rest phase. In fact after the activity phase, the Eeac values decrease rapidly to almost 0 but the body still dissipates a decreasingly important amount of energy.

2.3 Field Study

The conducted field study aims at collecting detailed information about the physiological interdependencies and their correlation with the workload. Thereby several physiological body reactions, like the consumption of oxygen, the breathing rate and the heart rate, etc., are measured during the load test and saved for offline analysis with reference to the predefined physical performance.

2.3.1 Field Study Procedure

Each test person undertakes two load tests on a treadmill ergometer. The first test is conducted with only the sensor shirt and a spirometer, which aims at validating the sensor data of the evaluation system and determining the energy expenditure of the body out of the sensor data through analyzing the correlation between these data and the reference data of the spirometer. In the second test, each test person wears the whole evaluation system (including cooling vest). Through this test, a verification of the suitability of the evaluation system for daily use and a validation of the implemented algorithm for active body climate control can be done.

The test procedure has to be conceived in a way that it makes it possible to compare the results of the load tests related to different test persons. Therefore a low workload level in the beginning of the test and short workload phases, which not exclude the reaching of a bio-physiological steady state status, need to be considered. According to (Wahlund, 1948), an absolute steady state status for light up to middle workload is reached after 6 minutes. Investigations of the sports university in Köln / Germany show that 90 up to 95% of the steady state status can be registered already after 3 minutes of the beginning of a constant workload (Knipping, 1953). For the conducted load test, a tradeoff is met analog to (Hollmann, 1963). After a baseline phase of 5 minutes, an intensity level of 6 km/h can be set at the treadmill ergometer for the period of time of 5 minutes followed by an increase of the intensity level with 1km/h. After the last test phase, which corresponds to an intensity of 11 km/h, the test person can rest for 5 minutes.

2.3.2 Test Person Feedback Form

During the study, subjective feedback from the test persons is collected by means of a test person feedback form. This latter includes general questions before the beginning of the load test dealing with the performance anamnesis (general fitness, physical and mental state on the day of testing, feeling of the room climate, etc.) and recording the individual physiological data of each test person, such as age, body height, weight, etc. and the climate in the room of the study (temperature, moisture, etc.).

During the load test with cooling vest, the actual wearing comfort of the vest and the local thermal comfort at the chest, the abdomen and the back are registered at every phase of the test.

After the end of the test, the test persons give their feedback related to the absolved test and to the test settings, for instance the evaluation system and the efficiency of its active climate control.

2.3.3 Test persons

The test persons are 11 high school students (males). Their age ranges between 21 and 30 years. Two test persons were not able to run the second test with the cooling vest. In addition one dataset from the test with cooling vest was discarded due to the loss of data after the reset of the control board. In fact a short circuit at the wrist-band feedback interface occurred due to an excessive generation of sweat and a lack of a protective layer.

3 RESULTS

3.1 Cooling Algorithm

To evaluate the quality of the cooling algorithm, the averaged level of the algorithm (Alg_{Level}) over all datasets is compared to the averaged user adjusted ventilation level ($Vent_{Level}$). Alg_{Level} increases with the physical load during the exercise and thus the need for cooling. The deviation between Alg_{Level} and the user adjusted value can in good approximation be interpreted as an offset failure. Further investigations show that the expected mean skin set point-temperature Tsk_{m0} varies with different environmental conditions. To improve the algorithm, Tsk_{m0} is adapted to the mean value (30°C) from the measurement data from the field study. The resulting ventilation level Alg_{Level_new} shows a good dynamic and stationary accuracy.

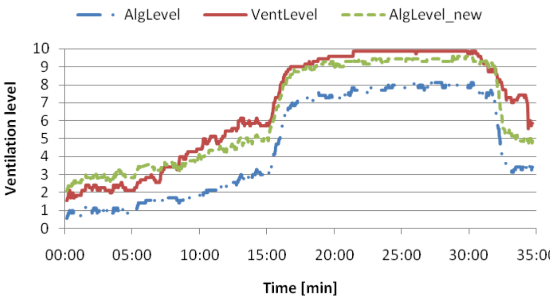
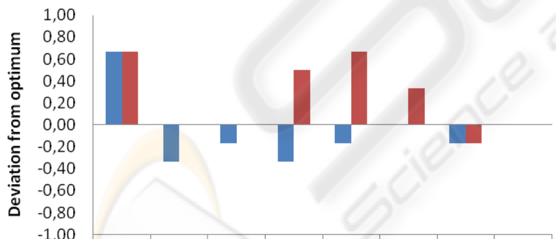


Figure 4: Evaluation of the implemented cooling algorithm; comparison of the different ventilation levels.

The evaluation of the feedback regarding the thermal sensation during the load test with active cooling gives information about the distribution of the cooling capacity. Since the cold air is aspired at the lower back of the cooling vest, the thermal sensation tends to be too cold at that area. With higher loads, the thermal sensation at the chest is getting hotter because the air warms up and is almost saturated and therefore insufficiently cools the chest.



	0	5	10	15	20	25	30	35
back	0,67	-0,33	-0,17	-0,33	-0,17	0,00	-0,17	0,00
chest	0,67	0,00	0,00	0,50	0,67	0,33	-0,17	0,00

Measurement time point [min] and deviation [+/hot; -/cold]

Figure 5: Evaluation of the feedback of the test persons.

3.2 Validation of the Sensor Data

3.2.1 Temperature Sensors

To analyze the temperature sensor data, a dataset is being examined. In figure 6 one could see that the temperature sensors can be affected by the dynamic of the body motion. In particular between 15 minutes, where the test person changes from walking to running and the end of the exercise at 35 minutes, the measured temperatures at the abdomen and the chest decrease unlike expected. It seems that the textile integrated temperature sensors loose direct contact to the skin, which causes a temperature drop.

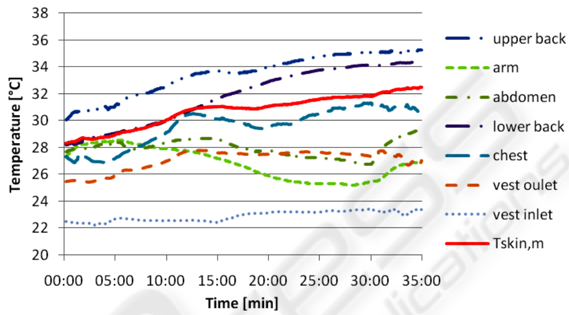


Figure 6: Temperature distribution for a test person.

3.2.2 Relative Humidity Sensors

Since the relative humidity is a function of the local temperature, the reliability of the temperature measurement has to be taken into consideration during the analysis. Therefore the body motion is also influencing the humidity measurement through the temperature deviation. At the End of the exercise the humidity values at the lower back and the chest are falling. This is caused by an increase in the local temperature and a high level of the ventilation.

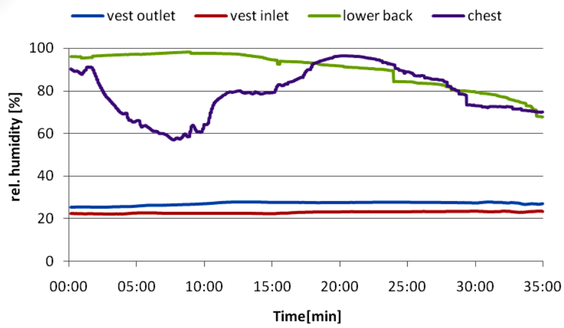


Figure 7: Relative humidity distribution for a test person.

3.2.3 Acceleration Sensor

From the raw data of the acceleration sensor, the Eeac value is calculated. As can be seen in figure 8, the signal is not directly used as a control input due to its strong noise and its offset. To compensate the offset the corresponding Activity equivalent acceleration (Aeac) signal is calculated.

$$Aeac = |Eeac - 1| \quad (7)$$

The resulting Aeac signal is filtered to reduce the noise.

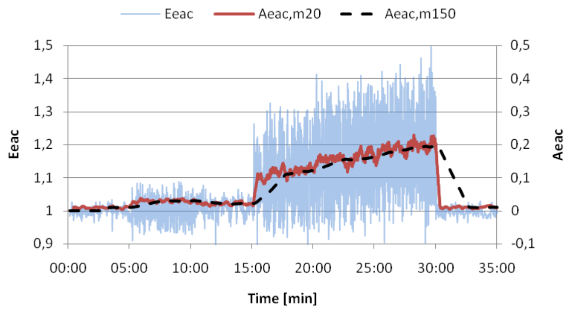


Figure 8: Raw and post processed acceleration data for a test person.

3.2.4 Breathing Sensor

To evaluate the results of the breathing sensor (BRT_Shirt) the measured rate is compared to the rate measured with the spirometer (BRT_Spiro), which can be seen as reference value due to its high accuracy. As figure 9 shows, both measurements match very well. One also could observe that the measured breathing rate has a slight latency only at phases with high dynamic. This latency is caused by the post processing of the raw signal with a median filter. In the first design of the regulation algorithm the breathing rate is not included in obtaining AlgLevel. In fact the determination of the breathing time volume, which results out of the product from th breathing rate and the breathing depth and which correlates directly with the energy expenditure (Hollmann, 2006), cannot be determined out of the measured signal. In addition the breathing sensor is used only on the chest and therefore may not provide reliable results in the case of abdominal breathing.

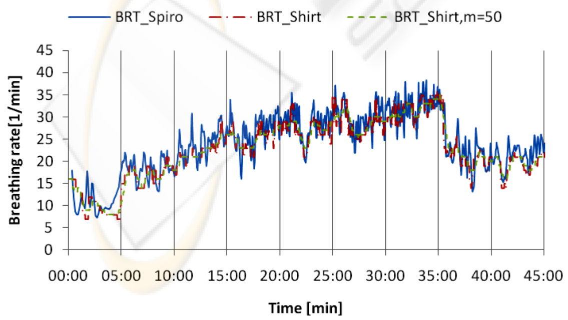


Figure 9: Comparison of the breathing rate data (BRT_Shirt and BRT_Shirt,m50) with the data from the spirometer (BRT_Spiro) for a test person.

3.2.5 Energy Expenditure

From the spirometer measurement of the O_2 consumption, an energy equivalent can be calculated, knowing that the human body needs 1l O_2 for the conversion of 20.9 kJ (Hollmann, 2006).

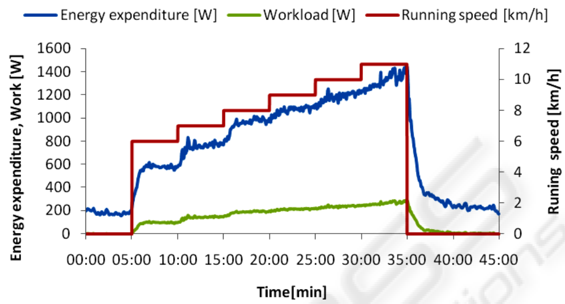


Figure 10: Workload and energy expenditure during the load test of a test person.

3.2.6 Regression Analysis

To determine the relation between the measured vital parameters and the energy expenditure out of the spirometer data, a correlation analysis is done. Out of it, the signals with the highest correlation are used in a regression analysis in order to approximate an analytical functional relation. For that purpose, the linear function coefficients are estimated with the robust least mean square method and a confidence interval of 95%. Input data are the energy expenditure and the corresponding sensor values for all datasets.

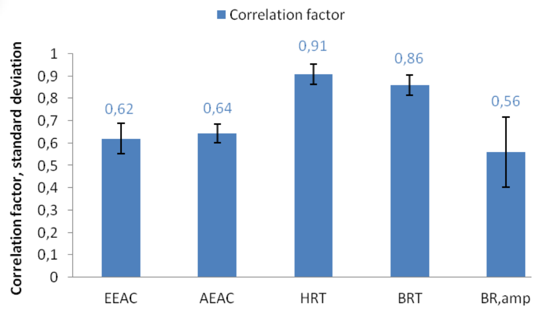


Figure 11: Correlation analysis between the measured vital parameters and the energy expenditure.

Heart Rate

The heart rate is directly influenced by physical stress due to the higher blood flow. Therefore the heart rate and the energy expenditure are strong correlated. In (Hollmann, 2006), a linear relation of first degree is postulated, which suits our results.

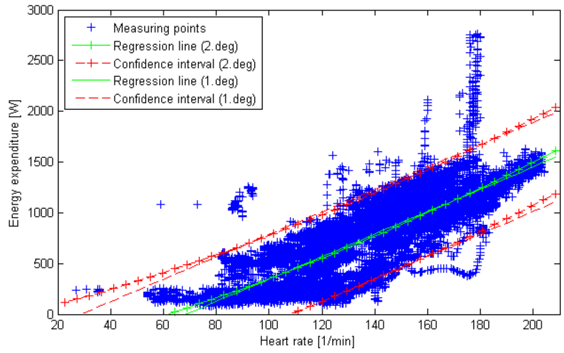


Figure 12: Regression analysis between the heart rate and the energy expenditure.

Breathing Rate

The correlation between the breathing rate and the energy expenditure is accounted by the linear rise in oxygen demand. To meet the demand, the minute volume can be raised either through faster or deeper breathing. Thus a variation of the breathing depth is intensified used at breathing rates of 15-30 [1/min] (Hollmann, 2006). There the variation from the linear approximation is higher.

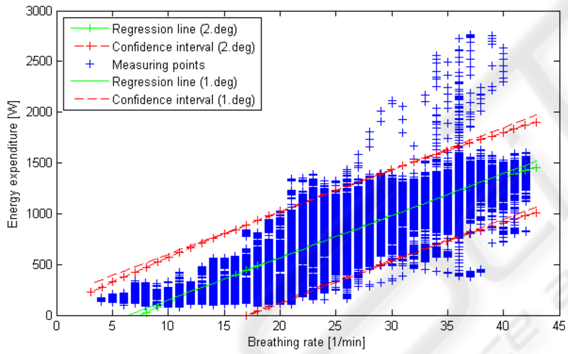


Figure 13: Regression analysis between the breathing rate and the energy expenditure.

Acceleration

For the mapping of the acceleration data, a first degree function is not appropriate. Especially at low acceleration values, a higher gradient is needed to meet the constraint that the energy expenditure at rest (AEAC ~ 0) equals the measured average measured value (~ 165 W). A function of third degree is used. Functions of higher degree cannot significantly improve the results. Unlike the heart rate and breathing rate, the acceleration is influenced by the nature of the load. Therefore, it has to be checked if the estimated relation is valid for other load patterns.

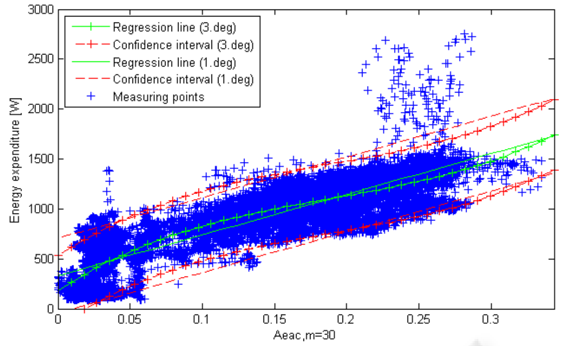


Figure 14: Regression analysis between the acceleration data and the energy expenditure.

4 DISCUSSION

In this work a regulation algorithm for active body climate control is heuristically conceived and tested with an evaluation system by conducting a field study. The validation of the current regulation algorithm shows quite gut results. Nevertheless, more data are needed in order to take into account the individual characteristics of different test persons and different environmental conditions. Out of the second part of the field study, where a spirometer has been used as a reference measurement for the body energy expenditure, a correlation and regression analysis between the sensor shirt data and the spirometer data shows a good quality of the post processed sensor data. In addition, analytical equations are determined in order to approximate the actual body energy expenditure out of the sensor data. This finding can now be used for a more accurate and systematic regulation algorithm, which implements a data fusion of the measured vital parameters and estimates the heat energy that needs to be transported away from the body surface. In combination with the estimated heat losses, derived from temperature, humidity and clothing isolation, it is possible to equalize the heat balance by calculating the appropriate ventilation level.

Besides, the design of the evaluation system needs to be optimized according to the feedback of the test persons during the field study: better fitting of the cooling vest, more ventilation resources with a better distribution, etc. Last but not least, a design of a wireless body area network (WBAN) with more sophisticated textile integration techniques could increase the comfort of the cooling system and its ease of use.

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