Comparison of a Sensorized Garment and Activity Trackers with a Mobile Ergospirometry System Concerning Energy Expenditure

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Abstract: Energy expenditure is an important parameter during the performance of physical activity. An algorithm is presented calculating the burnt calories by three given parameters: heart rate, respiration rate and movement. These three vital parameters are provided by the FitnessSHIRT system which was developed by the Fraunhofer IIS. A study was performed to compare the calculated values of the energy expenditure with a reference system based on ergospirometry, an on-body monitoring system and two commercially available activity trackers. Compared to the reference system the developed algorithm, based on the parameters derived by the FitnessSHIRT, reaches a deviation of 18.0 % during running and 18.9 % during cycling.

1 MOTIVATION

Obesity and overweight are a big challenge for future's society and the resulting consequences concerning health (WHO, 2015). For affected people the knowledge about their actual energy expenditure (EE), indicated in kcal/h is a significant parameter. Moreover this is what people motivates to quantify themself (Nißen, 2013).

The measurement of a person's physical effort is often performed by using lookup tables (Kent, 1997). Based on these tables athletes are able to estimate their energy expenditure on the basis of parameters like body height, body weight and their performed activity. As only a few parameters are considered, the lookup table just provides a rough estimation of the EE by a specific athlete. Another disadvantage is the increased demand for memory space.

The gold standard for the measurement of EE is the doubly labelled water method based on the carbon metabolism in the human body (Mueller et al., 2010). This method is, due to its complexity, often not applicable in practice, e.g. in the field of exercise physiology. Therefore, the most widespread method for measuring the EE is the ergospirometry (ESM) based on the indirect calorimetry (Mueller et al., 2010). Thereby, the breathing gases of athletes are analyzed for the estimation of the EE by applying a breathing mask. Hence the ESM is nowadays mobile applicable, the uncomfortable mask and the high costs make it unattractive for the usage in mass sports. However, ESM was used in this study as the reference method.

Several in the market available fitness trackers promise a reliable measurement of the EE. Most of these devices are either worn on the wrist or on the hip whereby an integrated accelerometer detects the movement of the user. Some of them also measure the heart rate (HR) by an optical sensor and additional personal information like age, gender, body weight and height of the user has to be entered. Out of all these parameters an estimation of the EE is calculated, e.g. after a training session.

The FitnessSHIRT system is a development of the Fraunhofer Institute for Integrated Circuits IIS (Hofmann, 2015). It provides a comfortable, longterm and accurate measurement of heart activity, respiration and movement of the user.

In this work an algorithm for the calculation of the EE, based on the parameters measured with the FitnessSHIRT, was developed. The quality of the algorithm has been evaluated by comparison to the EE values gained by the ESM and commercially available fitness trackers.

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2 SYSTEMS

2.1 Fraunhofer FitnessSHIRT

The FitnessSHIRT, a development by the Fraunhofer IIS, is a textile with unobtrusive integrated sensors for measuring a 1-channel ECG and the thoracic movement of the chest to determine the respiration frequency (Figure 1). Therefore, two conductive textile electrodes and a flexible respiration belt were integrated into a compression shirt. An attachable sensor unit, either applied in the chest region or between the shoulders, gathers the sensors raw data. Based on this raw data reliable and stable algorithms calculate secondary parameters like heart rate (HR), heart rate variability (HRV) and respiration rate (RR). Additionally, an integrated accelerometer records the movement of the wearer. By means of the acceleration data an implemented algorithm detects movement patterns like walking or running as well as the person's posture.

Figure 1: Fraunhofer FitnessSHIRT.

2.2 CareFusion Oxycon Mobile

The mobile ergospirometry, a diagnostic method to measure the composition of the breathing gases during physical strain, is enabled by the Oxycon Mobile (CareFusion, 2015). The behaviour of the cardiovascular system, heart activity, breathing performance and metabolism as well as cardiopulmonary capability is analyzed in a qualitative and quantitative manner. As this method is classified as a gold standard for measuring EE it provides the reference data.

The entire system consists of a shoulder belt with applied O_2/CO_2 analyzers and a transmitter, a telemetry unit (receiver) with calibration module, a breathing mask with TripleV-Sensor and a chest sensor strap to measure the heart rate.

With the aid of the associated software application the acquired data can be depicted instantly and saved for a more detailed post analysis.

2.3 BodyMedia SenseWear

The SenseWear MF armband by BodyMedia (BodyMedia, 2015) is applied to the left upper arm, so that the electrodes are directly applied on the wearers skin. By means of the integrated sensors motion, steps, galvanic skin response, skin temperature and heat flux is detected. Based on the gained data and an integrated algorithm the system calculates the EE (kcal/min) over a given time.

2.4 FitBit Flex and FitBit One

The FitBit Flex and the FitBit One are two activity trackers to monitor and record the all-day activity by tracking steps and estimating the burned calories (FitBit, 2015). Therefore, both trackers have an integrated 3-axis accelerometer. Additionally the FitBit One provides an altimeter to calculate the taken steps or stairclimbs.

3 METHODS

In total 13 male test persons aged between 19 and 51 years participated in the trial (see Table 2). The group had a mean age of 33.9 years (standard deviation σ = 9.9 years), an average body height of 181.0 cm (σ = 6.0 cm) and a mean weight of 83.9 kg (σ = 11.1 kg). The body mass index (BMI) was calculated with 25.5 kg/m^2 (σ = 2.5 kg/m^2) with an average body fat percentage of 16.5 % (σ = 6.3 %).

In order to generate valid data packages the 13 subjects had to perform the following test run. The first step was to analyze the body composition with the aid of the InBody 770 body composition analyzer (InBody, 2015). The measurement systems were applied to the subjects in the following order:

- Heart rate sensor strap Polar H7 (heart rate data used by Oxycon Mobile)
- FitnessSHIRT with correct size to achieve good skin contact
- Activity tracking modules FitBit Flex (wrist) and FitBit One (collar of shirt)
- SenseWear MF armband (left upper arm)
- CareFusion Oxycon Mobile

The complete application of the systems can be seen in Figure 2.

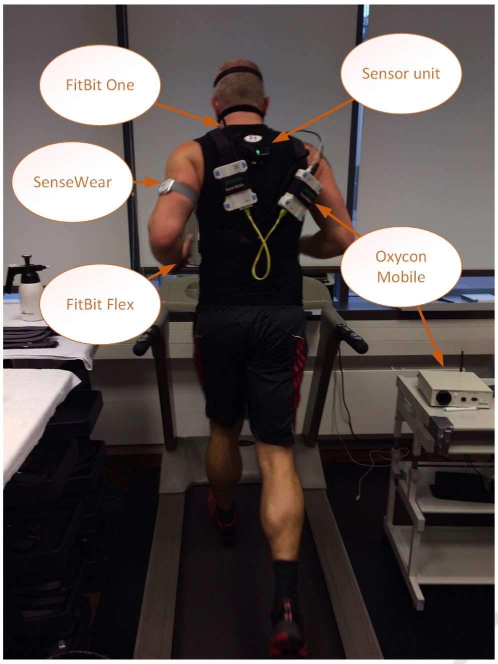

Figure 2: Overview of all applied systems used in the trial.

Two test scenarios had to be fulfilled during the trial by each subject, one incremental step test on the treadmill and one on the cycle ergometer. The given test protocols are presented in Table 1.

Table 1: Procedure of incremental step tests.

	Treadmill	Ergometer
Starting load	10 km/h	130 Watt
Duration of first period	5 min	3 min
Increase (every 3 min)	1 km/h	30 Watt

The test run starts at 10 km/h (treadmill) and 130 Watt (ergometer), respectively. In contrast to the treadmill with a starting interval of 5 minutes the first period on the cycle ergometer takes 3 minutes. Subsequently, every 3 minutes the load was increased by 1 km/h on the treadmill and by 30 Watt on the cycle ergometer. The pedal frequency was defined to 70 1/min constantly throughout the whole test.

Each data sample was stored in pseudonymous form to assure the security of the personal data of the subjects.

4 ALGORITHM DEVELOPMENT

4.1 Idea

The main idea of the algorithm was to show an improvement by using three measured parameters compared to standard methods measuring only one parameter. Since our system is able to record respiration, heart activity (ECG) and movement (acceleration), which are all related to the energy usage of the body, an algorithm considering all these parameters was developed. This results in several advantages: If one parameter does not provide reliable data (e.g. no data at all or implausible data), a backup is still given and can use the other two parameters. The different parameters can also be weighted based on the plausibility.

Table 2: Overview test group.

Age [years]	Height [cm]	Weight [kg]	BMI [kg/m^2]	Body fat [%]
37	177	76.7	24.5	17.0
51	177	73.4	23.4	13.9
34	190	98.5	27.3	23.0
37	194	96.8	25.7	20.3
46	177	90.2	28.8	28.3
19	182	65.6	19.8	8.1
19	180	84.1	26.0	10.1
26	173	72.5	24.2	9.9
27	180	82.4	25.4	12.9
33	181	93.8	28.6	24.7
46	186	98.0	28.3	19.6
36	181	85.3	26.0	14.8
30	175	72.8	23.9	11.6

4.2 Preprocessing

Based on these ideas the raw data of three sensors as well as a reference system are used to develop the following algorithm using MATLAB.

4.2.1 Interval of Energy Values

The reference system gives one energy value per minute. Therefore this frequency is the reference for the estimated energy values.

4.2.2 Electrocardiogram

A complete ECG is recorded. In a first step the RR intervals are detected and this data is used to calculate the heart rate (Tantinger et al., 2012). Then the data set is divided in parts with a duration of one minute. Each part is sorted and the highest 20 % and the lowest 20 % of the values are removed to ensure that no extreme values are influencing out results. An average of the remaining 60 % is used as a representative value for each minute. This representative value is used for further calculations.

4.2.3 Respiration

Again raw data is available representing a complete curve. In a first step the respiration rate is detected and after that the same ideas as described above for the ECG will be used: Divide the data into one-minute-blocks, remove extreme values and average the remaining 60 % for getting a representative value. This representative respiration rate value is used for further calculations.

4.2.4 Movement

The sensor records three axis of acceleration. An intensity-value was calculated, which represents how much movement and accelerations influenced the signal. Since only one axe had a relevant correlation of 0.48 with the reference values, this axe was used. Again a representative value was gained by averaging with a FIR-Filter and extracting one value per minute from the filtered signal.

4.3 Calculating Energy Values

There are three values for each minute: An average heart rate, an average respiration rate and a movement intensity representative. The heart rate and the respiration rate can both be used as an important input value for energy estimation. Both formulas are based on the same idea to transport oxygen by breathing into the lungs and this oxygen will be transported by the blood through the body. Depending on the amount of used energy, the oxygen usage of the body changes which also results in a change of respiration rate and heart rate. An additional effect was considered, about the body using the oxygen more efficient if higher amounts of oxygen are needed.

Therefore the formula for both parameters is based on the same core formulas:

$$EE = O_2 \cdot EF \cdot \frac{E}{O_2} \quad (1)$$

EE: estimated energy [kcal]
O_2: amount of oxygen transported through the body calculated in the following formulas [ml]
EF: efficiency-factor based on heart rate
$\frac{E}{O_2}$: energy per oxygen can be calculated from chemical formulas [kcal/ml]

Now we distinguished between respiration and the heart rate to get two values for the used oxygen. Based on the respiration rate we get the following formula:

$$O_2 = O_{2\text{IN}} - O_{2\text{OUT}} = RR \cdot LV \cdot \Delta O_{2\%} \quad (2)$$

O_2: oxygen used by the body [ml]
O_{2IN}: oxygen in the air coming into the body [ml]
O_{2OUT}: oxygen in the air coming out of the body [ml]
RR: respiration rate [1/min]
LV: lung volume [ml]
$\Delta O_{2\%}$: difference between the amount of oxygen, when breathing in and out. Usually the difference is 5 % (the amount of oxygen is reduced from 21 % to 16 % when breathing)

The formula for the heart rate is similar:

$$O_2 = B \cdot \frac{O_2}{B} = HR \cdot HBV \cdot \frac{O_2}{B} \quad (3)$$

O_2: oxygen used by the body [ml]
B: amount of blood transported through the body [ml]
$\frac{O_2}{B}$: amount of oxygen that can be transported in the blood [ml/ml]
HR: number of heart beats [1/min]
HBV: heart beat volume, the amount of blood that is transported with each beat [ml]

In a first approach, the following assumptions were made:

- The HBV was assumed constant as well as the LV (both were calibrated with a subset of data). A further idea for later approaches might be to consider age, sex, height, weight or similar aspects for calculating each volume.
- The amount of used oxygen ($\Delta O_{2\%}$) was set to 5 %. This value was used from literature (Mueller, 2001).
- The efficiency-factor was described in literature for two heart-rate-values. Therefore all values above and below were kept constant, all values between were linear interpolated.

These formulas were used to get two estimates for the used energy.

The simple approach for the movement was not sufficient enough to calculate a value only based on the movement signal, but it was sufficient to estimate a difference. Therefore the actual value of the movement representative was compared with the previous one. Then this relation was used to estimate the change in the energy consumption:

$$EE_{\text{mov(t)}} = EE_{\text{(t-1)}} \cdot \frac{mov(t)}{mov(t-1)} \quad (4)$$

t, t-1: time points (actual, previous)
EE(t-1): previous estimated energy consumption (of all parameters)
mov(t): movement-intensity representative for the time point t

This approach is surely not optimal, especially it ignores the fact that there is a basal metabolic rate.

But it still gives an estimate for energy consumption, especially under strong movement.

4.4 Plausibility

Now it is necessary to combine these three estimated values to more reliable estimated value. The trivial idea just to average them has a major disadvantage: If just one value is erroneous the complete average is corrupted, e.g. if one value is not measured, what will result in a zero-value, the average will be 33 % too small. Therefore it is obvious that some checking of the plausibility of these values is necessary. In this approach the plausibility[1] was not binary, but values from 0 to 10 were given. This values based on the following checks:

- Difference between the actual value and the previous value. The higher the difference, the lower the plausibility.
- Threshold values were used to check if the value itself was plausible. Especially if a very low energy consumption (below basal metabolic rate) or a very high energy consumption was detected, the value of plausibility was set to 0.
- The similarity of the estimated energy values. If two values are similar and the third one is different, it is assumed that the similar ones are more plausible. This idea is not yet implemented in our first approach.

Because the values derived from movement had less direct connection to the energy consumption (e.g. the correlation was below 0.5, the basal metabolic rate was not considered in the formula), the maximum plausibility was set to 5, the values derived from heart rate and respiration rate had, as mentioned above, a maximum of ten.

And since some values could not be calculated for the first value, we started the calculation as follows:

$$EE_{(1)} = \frac{EE_{\mathrm{HR(1)}} + EE_{\mathrm{BR(1)}}}{2} \tag{5}$$

And then for $t \geq 2$:

$$EE_{(t)} = \frac{EE_{\mathrm{HR(t)}} \cdot P_{\mathrm{HR(t)}} + EE_{\mathrm{BR(t)}} \cdot P_{\mathrm{BR(t)}}}{P_{\mathrm{HR(t)}} + P_{\mathrm{BR(t)}} + P_{\mathrm{MOV(t)}} + 0.01} + \frac{EE_{\mathrm{MOV(t)}} \cdot P_{\mathrm{MOV(t)}} + EE_{\mathrm{(t\text{-}1)}} \cdot 0.01}{P_{\mathrm{HR(t)}} + P_{\mathrm{BR(t)}} + P_{\mathrm{MOV(t)}} + 0.01} \tag{6}$$

Therefore a weighted average of the energy estimates is calculated. The last part of the sum ensures that the formula still result in reliable values if all other plausibility values are 0. In this case the previous value is used, in other cases the small plausibility has almost no influence. If this value should be shown on a display or at least a warning should be added depending on the use case.

[1] We later were informed that our concept of plausibility has similarities to the Dempster-Shafer theory(Shafer et al., 1976). During the development of the algorithm we did not consider those findings but will check if they help to improve further versions

5 RESULTS

Based on the developed algorithm the energy expenditure was calculated for the FitnessSHIRT system. The calculated EE values of all measurement systems were compared to the reference ergospirometry system. The results are presented as percentage deviation to the reference in Table 3. In the first two lines the EE were calculated by taking either only the heart rate (FS_HR) or only the respiration rate (FS_RR) into account. The result using all three measured parameters (heart rate, respiration rate, movement data) is given in line three with FS_Comb (highlighted green). As the calculation of the EE is not supported by the FitBit systems during cycling the stress test for the ergometer was not feasible.

Table 3: Percentage deviation of the systems from reference (ergospirometry).

	Treadmill	Ergometer
FS_HR	24.6 %	19.6 %
FS_BR	47.7 %	45.1 %
FS_Comb	18.0 %	18.6 %
SenseWear	21.6 %	28.1 %
FitBit One	18.1 %	n/a
FitBit Flex	21.9 %	n/a
Wahoo	37.2 %	21.8 %

With a deviation of 18.0 % (treadmill) and 18.6 % (cycle ergometer) the FitnessSHIRT system in combination with the presented algorithm achieves the most accurate proposition by combination of heart rate, respiration rate and movement data. Hence, it is clearly visible that a calculation only based on a single parameter is not applicable with the developed algorithm. The calculation based on the respiration rate has the highest deviation of all applied systems with a value of of 47.7 % (treadmill) and 45.1 % (cycle ergometer).

In Figure 3 the comparison of the ergospirometry system to the FitnessSHIRT system is represented for only one data set. The calculated EE values for the treadmill stress test of proband 11 are visualized over a period of 15 minutes.

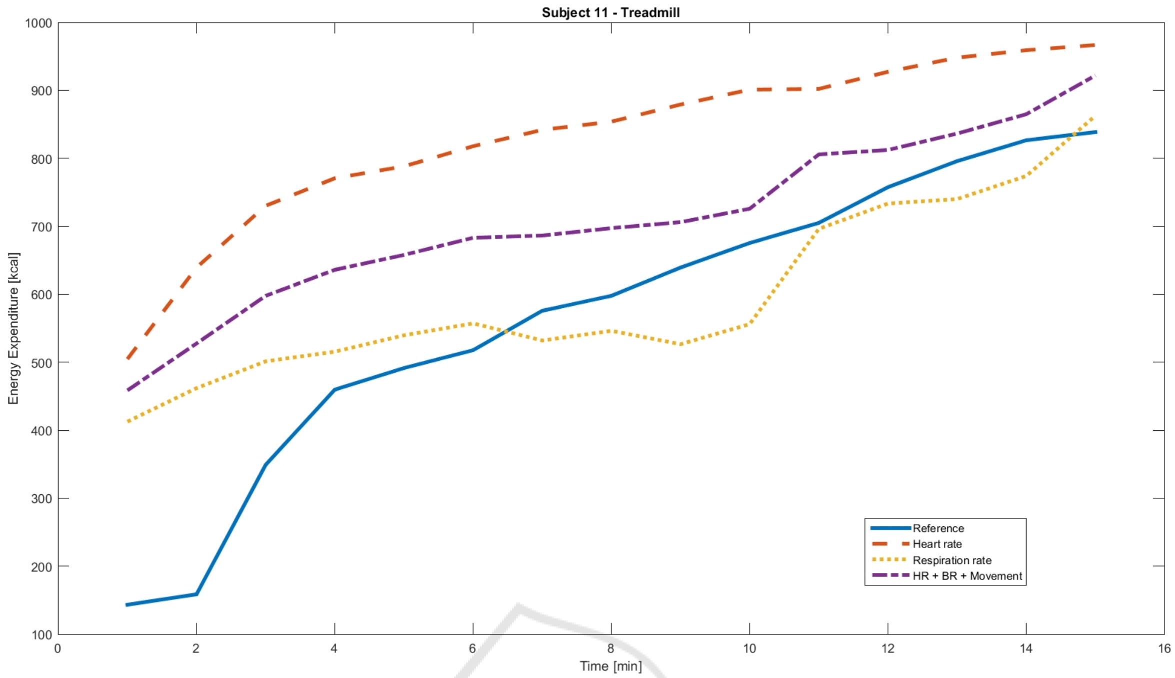

Figure 3: Reference data compared with calculated FitnessSHIRT data concerning energy expenditure.

6 CONCLUSION AND OUTLOOK

An algorithm to calculate the energy expenditure with the Fraunhofer FitnessSHIRT system is presented. The acquired data comprises heart rate, respiration rate and movement data on which the calculation is based. In a first trial with 13 subjects the basic functionality of the algorithm was verified.

Although the basic algorithm showed good results, several improvements can be realized in future research: As mentioned above, a further consideration of the movement data would lead to a more accurate value of the EE. In addition there are possibilities to calculate a more detailed plausibility value, some options are already mentioned in this paper. Also the considerations about some data of the patient should be taken into account. Right now the algorithm assumes that each person has the same blood volume transported during each heart beat and the same air volume used during respiration. Considering age, height and weight in the algorithm should improve the quality of output. A personal calibration might result in reliable values, but this process is more complex and might not be applicable in all use cases.

Another approach will be a more extensive trial with a larger number of subjects. Therefore, it would be possible to divide the complete test sample into several groups. Different parameters, e.g. age, body mass index (BMI) or body fat percentage, can be evaluated more specific and it could be examined if those parameters differ concerning the calculation of the energy expenditure.

In this trial only male participants were tested as there is no FitnessSHIRT for women developed at the moment. Consequently we have to realize a sensor shirt in order to address this target and user group. Hereby particular attention has to be paid to the anatomical differences of the chest. It is mandatory to have enough pressure on the electrodes to guarantee continuous skin contact for high signal quality.

In conclusion, the presented system gives the user an easy-to-use and accurate value of the burnt calories during exercises compared to the used reference. Based on the promising results, the presented method offers a reliable measurement of the physical effort without the need of cost-intensive reference systems.

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