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Validation of SenseWear Armband in children, adolescents and adults

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Abstract

Background: SenseWear Armband (SW) is a multisensor monitor to assess physical activity and energy expenditure. Its prediction algorithms have been updated periodically. **Purpose:** To validate SW in children, adolescents and adults. **Methods:** The most recent SW algorithm 5.2 (SW5.2) and the previous version 2.2 (SW2.2) were evaluated for estimation of energy expenditure during semi-structured activities in 35 children, 31 adolescents and 36 adults with indirect calorimetry as reference. Energy expenditure estimated from waist-worn ActiGraph GT3X+ data (AG) was used for comparison. **Results:** Improvements in measurement errors were demonstrated with SW5.2 compared to SW2.2, especially in children and for biking. The overall mean absolute percent error with SW5.2 was 24% in children, 23% in adolescents and 20% in adults. The error was larger for sitting and standing (23-32%) and for basketball and biking (19-35%), compared to walking and running (8-20%). The overall mean absolute error with AG was 28% in children, 22% in adolescents and 28% in adults. The absolute percent error for biking was 32-74% with AG. In general, SW and AG underestimated energy expenditure. However, both methods demonstrated a proportional bias, with increasing underestimation for increasing energy expenditure level, in addition to the large individual error. **Conclusions:** SW provides measures of energy expenditure level with similar accuracy in children, adolescents and adults with the improvements in the updated algorithms. Although SW captures biking better than AG, these methods share remaining measuremens errors requiring further improvements for accurate measures of physical activity and energy expenditure in clinical and epidemiological research.

Keywords: Physical activity, energy expenditure, indirect calorimetry, multisensor, ActiGraph.

Introduction

Objective measurement of physical activity has been a challenge, where single-sensor devices (e.g. accelerometers) have difficulties to capture the range of activities and intensities (Hills et al. 2014). In 2001, the multi-sensor device SenseWear Armband was released, using advanced algorithms to intergrate signals from different types of sensors to estimate energy expenditure. These algorithms have been updated periodically for improved accuracy for more activities and in different age-groups. The specific changes in the algorithms are largely unknown, being proprietary information.

The first validation studies of SenseWear in adults doing structured activities demonstrated that contextual algorithms provided better estimates of energy expenditure compared to the general algorithms (Jakicic et al. 2004), that an accurate estimate of biking could be achieved (Fruin & Rankin 2004; Jakicic, Marcus 2004), and that SenseWear captured vigorous intensity better than the ActiGraph accelerometer (King et al. 2004). With subsequent updated algorithms, SenseWear showed somewhat better estimates of energy expenditure than ActiGraph also for free-living activities, including biking and activities of vigorous intensity (Berntsen et al. 2010). However, in protocols including a wider range of running and biking intensities, SenseWear showed increasing underestimation of energy expenditure for increasing activity intensity (Drenowatz & Eisenmann 2011; Koehler et al. 2011). This proportional bias was confirmed under free-living conditions (Johannsen et al. 2010; Koehler, Braun 2011; St-Onge et al. 2007), and continued with the most recent algorithms updates (van Hoye et al. 2014). In a comprehensive evaluation of the most recent algorithms updates during structured and semi-structured activities, there were small improvements compared to previous algorithms version, with some activity-specific changes (Bhammar et al. 2016). For example, the bias of biking moved towards larger underestimation of energy expenditure. This study could not confirm the proportional bias previously observed.

The first validation study of SenseWear in children performing a mixture of structured and semi-structured activities demonstrated underestimation of energy expenditure for most activities, including biking, and there was a proportional bias with energy expenditure level (Arvidsson et al. 2007). These results were in contrast to the performance of previous algorithms version, where energy expenditure was generally overestimated (Dorminy et al. 2008). This transition in the measurement bias was confirmed in subsequent studies comparing two algorithms versions during structured activities (Calabró et al. 2009) and during free-living (Arvidsson et al. 2009). Two studies comparing the most recent algorithms updates with the previous algorithms for semi-structured activities showed a general reduction in measurement bias, with the largest improvement for biking (Lee et al. 2016; van Loo et al. 2016). Still, SenseWear generally underestimated energy expenditure. One of the studies demonstrated a proportional bias with energy expenditure level (van Loo, Okely 2016), while the other did not (Lee, Kim 2016). A recent free-living study confirmed the proportional bias (Calabró et al. 2013).

The periodical updates of the SenseWear algorithms have improved measurement accuracy, but the errors remain large. Optimally, this conclusion can be drawn by comparing the measurement errors not only to previous versions of the same method, but also to established alternative methods. Another question is whether SenseWear can be used to compare physical activity across age-groups, which requires similar measurement accuracy. Previous studies in children or in adults indicate that SenseWear underestimates energy expenditure in children (Calabró, Stewart 2013; Lee, Kim 2016; van Loo, Okely 2016), but overestimate energy expenditure in adults (Bhammar, Sawyer 2016). No direct comparison between age-groups has been performed. The present study aimed to validate SenseWear in healthy children, adolescents and adults.

Methods

Study design

Children, adolescents and adults performed semi-structured indoor and outdoor activities of various intensities in their natural environment. Similar activity types were used in the three-age-groups for comparability. Indirect calorimetry was used as reference for energy expenditure. Two versions of the SenseWear (SW) energy expenditure algorithms were evaluated: algorithm v2.2 in software v7.0 (SW2.2, released in 2009) versus algorithm v5.2 in software v.8.1 (SW5.2, released in 2014). The outcomes with the SW were compared to when energy expenditure was estimated using the waist-worn ActiGraph accelerometer (AG), which represents a simpler methodology and it is the most commonly used and evaluated activity monitor in research (Hills, Mokhtar 2014). This study was approved by the Ethics Committee of the region of Southern Denmark (S-2014-0068).

Participants

Thirty-six children in grade 3-4 and 31 adolescents in grade 8-9 were recruited from a local school in Odense, Denmark, by announcement e-mailed to the parents through the school adminstration. Thirty-nine adult participants were recruited among staff members at the Department of Sport Science and Clinical Biomechanics, University of Southern Denmark in Odense, Denmark by direct contact or by announcement in institutional news letters. Informed consent was received from all participants or their parents.

Energy expenditure

SenseWear Armband

The SenseWear Armband Mini (Bodymedia, Pittsburg, PA, USA) consists of a triaxial accelerometer and sensors for skin temperature, heat flux and galvanic skin responses. The patterns of signals from these sensors are combined to determine the type and intensity of activity. Proprietary algorithms including individual characteristics (age, sex, weight, height) are used to estimate energy expenditure each minute. The monitor was attached with the elastic strap around the non-dominant arm and collected data was processed in both software 7.0 and 8.1 using measured weight and heigh together with information about age, sex and dominant arm.

ActiGraph

ActiGraph model GT3X+ (ActiGraph, Pensacola, FL, USA) is a triaxial accelerometer recording data at a sampling rate of 30-100 Hz along the vertical, antero-posterior and medio-lateral axis with a dynamic range of ±6g. In the ActiLife software the data is processed to generate the outcome activity counts, which is a measure of the intensity of the activity performed. The activity counts have been calibrated for energy expenditure with the monitor at the right hip using indirect calormetry as reference. There are several algorithms to choose between for this position based on the older ActiGraph model AM7164, but few for the GT3X+. Santos-Lozano et al developed an algorithm for youths (12-16 yrs) and adults (40-55 yrs) using the vector magnitude (VM) of activity counts from model GT3X to calculate the MET-value (Santos-Lozano et al. 2013). Unfortunately, their study did not include individuals corresponding to the age of the youngest age-group in the present study. We applied their age-combined algorithm to all three age-groups:

$$\text{METs} = 2.7406 + 0.00056 \cdot \text{VM} - 0.008542 \cdot \text{Age} - 0.01380 \cdot \text{body weight}$$

Total energy expenditure can thereafter be calculated by multiplying the MET-value with resting energy expenditure. The GT3X+ monitor was set to sample data at 30 Hz and was attached in an elastic belt over the right hip. Activity counts in 10s-epochs were generated in ActiLife version

6.11.4 and aggregated into counts per minute for the energy expenditure calculations. The resting energy expenditures determined by Harrell et al in children 8-12 years old (7.15 $kJ \cdot kg^{-1} \cdot hr^{-1}$) and adolescents 13-18 years old (4.85 or 5.61 $kJ \cdot kg^{-1} \cdot hr^{-1}$ depending on age) were used to calculate total energy expenditure in these age-groups, and the commonly used definition of resting energy expenditure of 1.00 $kcal \cdot kg^{-1} \cdot hr^{-1}$ (or 4.18 $kJ \cdot kg^{-1} \cdot hr^{-1}$) was used for the adults (Harrell et al. 2005).

Indirect calorimetry

Metamax 3X portable metabolic gas analysis system (Cortex, Leipzig, Germany) was used to assess reference values of energy expenditure. It was attached to the body (back) in a vest system. The participants wore a face-mask where expired air was sampled for analyses on concentration of O_2 and CO_2 in the mixing chamber and where the Triple V turbine volume sensor measured the air flow. Air flow and two-points gas calibrations were performed before the sessions according to the manufacturer´s instructions. No restrictions concerning exercise or food intake before measurements were given to participants.

Procedure

The location of measurements and the activities included were selected to represent the natural environment and variation of position, movement and intensity of the participants (Table 1). For the children and adolescents, the activities were performed indoors and outdoors at the school area as well as at a walking/biking path outside the school area, and for the adults the activities were performed in the office premises and outdoors on the institutional sports arena. All equipment used was initiated and time-synchronized on one common computer close before each measurement. After arrival the participant was provided a description of the protocol and thereafter body weight was measured on a calibrated digital scale and body height using a stadiometer. The equipment was attached to the body and the measurement started after an adaption period of 10 minutes. Each activity lasted for 5 minutes. For the children and adolescents, walking and running were performed consecutively in the order of intensity without breaks. For the other activities and for all activities in the adults, there was a natural break of 2-5 minutes between each activity. Energy expenditure from all methods was calculated as the mean of the last 3 minutes of each activity.

Statistics

The measurement error ($kJ \cdot kg^{-1} \cdot min^{-1}$) was calculated as the difference between SW2.2/SW5.2/AG and indirect calorimetry (IC). This difference was divided by IC and multiplied with 100 to get percent error. Absolute percent error was calculated as the root of the square of the percent difference and is a quantification of the total magnitude of error. The mean percent error and mean absolute percent error were investigated as measures of validity at group-level and individual-level. Bar plots and Bland-Altman plots were used to display the results. In the Bland-Altman plots the error (y-axis) is presented across levels of energy expenditure (x-axis). We chose to set energy expenditure from IC on the x-axis. In addition, the degree of covariation in energy expenditure ($kJ \cdot kg^{-1} \cdot min^{-1}$) between SW2.2/SW5.2/AG and IC was determined by calculating intra-individual Pearson correlation. All statistics were performed in IBM SPSS Statistics 24.0 (IBM Corp, Armonk, NY, USA).

Results

Data from one child participant was excluded from analyses due to error in the calibration of Metamax 3X. Data from one adult participant was excluded from analyses due to extreme gas exchange values and another two adult participants due to lost SW data. Table 2 presents the characteristics of the three age-groups.

The first step was to get an overall view of the errors with SenseWear. Figure 1 presents in Bland-Altman plots the individual percent errors for all activities included and reveals some important features. First, there seemed to be only small improvements in the systematic bias with SW5.2 in the three age-groups, with some variation between individual activities, and there was a persistent large individual error. Second, the bias was proportional to the level of energy expenditure for most activities, with a negative slope. Third, the most apparent improvement in bias occurred for biking in children, but the individual error persisted. This improvement contributed to the reduction of the overall limits of agreement in this age-group. There seemed to be a slight improvement in the bias also for walking and running in children. Fourth, the underestimation of energy expenditure for sitting and standing persisted with SW5.2. Altogether, the overall bias and errors of SW5.2 seems more comparable between the age-groups. The overall bias was comparable to the AG, but the limits of agreement seemed smaller with SW5.2. AG showed a large systematic underestimation of energy expenditure for biking in all age-groups, which influenced the limits of agreement.

In the next step, we quantified the biases of the individual activities. Figure 2 presents the mean absolute percent error as well as the direction of the mean percent error (underestimation or overestimation). There were some improvements in the bias with SW5.2 for most activities in all three age-groups. The largest improvement occurred in children. The mean absolute percent error of all activities for SW2.2 and SW5.2 in this age-group was 37% and 24% (horizontal lines). The corresponding values were 26% and 23% in adolescents, and 25% and 20% in adults. In addition, the mean intra-individual correlation with IC improved considerably in children, reaching the same level as in the other age-groups; 0.73 to 0.91, compared to 0.90 to 0.93 in adolescents and 0.93 to 0.96 in adults. In children, the mean absolute percent error for biking improved from 59% to 32%. The corresponding values in adolescents were from 25% to 19%, and in adults from 41% to 22%.

For comparison, the mean absolute percent error of all activities and the mean intra-individual correlation with IC for AG was 28 % and 0.91 in children, 22 % and 0.83 in adolescents, and 28% and 0.82 in adults. There was a systematic underestimation of energy expenditure for biking with AG, with mean absolute percent error of 32% in children, 59% in adolescents and 74% in adults.

The pattern of the mean absolute percent error for SW5.2 was similar between the age-groups, with larger error for the sitting and standing activities (23-32 %) and for basketball and biking (19-35 %), compared to walking and running (8-20 %) (Figure 2). A somewhat similar pattern could be observed also for AG, with absolute percent error of 14-52 % for standing and sitting, 11-74 % for basketball and biking, compared to 10-34 % for walking and running.

Adding the energy expenditure of all activities (and consequently the errors of the individual activities) to a total duration of 40 minutes, resulted in no or minor improvement in the total mean absolute percent error with SW5.2 (Figure 3). The total absolute percent error was 12-19 % in the three age-groups with SW5.2, compared to 9-37 % with AG. SW5.2 underestimated the total energy expenditure by 1.97-3.44 $kJ \cdot kg^{-1} \cdot min^{-1}$ in the three age-groups ($p<0.001$ in all age-groups) (Figure 3). With AG the bias ranged from an overestimation of 0.82 $kJ \cdot kg^{-1} \cdot min^{-1}$ in children ($p<0.001$) to an underestimation of 2.64-5.97 $kJ \cdot kg^{-1} \cdot min^{-1}$ in adolescents and adults (both $p<0.001$). There was a proportional bias with negative slope for SW2.2 (R^2=0.54-0.85, all $p<0.001$), which remained with SW5.2, although reduced (R^2=0.36-0.63, all $p<0.001$). Still, the proportional bias was larger with AG (R^2=0.61-0.84, all $p<0.001$).

Discussion

This study in children, adolescents and adults demonstrated small improvements in the estimation of energy expenditure with SenseWear Armband algorithm 5.2. A notable improvement occurred for biking in children. SW5.2 provided estimates of comparable accuracy in children, adolescents and adults. Still, the bias varied depending on type of activity and level of energy expenditure, with large errors at individual level. The magnitude of the errors was in many cases similar to what could be observed for the simpler waist-worn ActiGraph accelerometer. SW5.2 was better in estimating energy expenditure for biking than ActiGraph. The mean absolute error of SW5.2 ranged from 8% during normal running up to 35% for basketball. SW5.2 underestimated energy expenditure during the 40 minutes protocol by 12-19%.

In the previous study in healthy adults by Bhammar et al (Bhammar, Sawyer 2016), SenseWear generally overestimated energy expenditure, including resting, with some improvement with SW5.2. No proportional bias related to energy expenditure level was observed. These results are in contrast to what was found in the present study. Possible explanations may be that the proportion of vigorous activities included was smaller in their study and they were performed at a lower intensity. Underestimation seems to appear above intensities corresponding to a running speed above 9 $km \cdot h^{-1}$ and a MET-value of 10 METs (van Hoye, Mortelmans 2014). The highest running speed in the study by Bhammar et al was 9 $km \cdot h^{-1}$ (Bhammar, Sawyer 2016). The mean running speed in the present study was estimated to 11 $km \cdot h^{-1}$ with a range of 8-14 $km \cdot h^{-1}$, and the mean MET-values were 11 for running and basketball and 8 for biking with a range of 6-15 METs for these activities. In addition, the sitting and standing activities were clearly underestimated in the present study with a proportional bias related to energy expenditure level. There were no restrictions concerning food intake or exercise before participation in the present study and there was a considerable inter-individual variation in the performance of the sitting and standing activities, which affected the energy expenditure level. It seems therefore that stricter resting conditions are assumed during sitting and standing with SenseWear, where energy expenditure is calculated from individual characteristics rather than using the heat-flow sensors. These stricter conditions may rarely be fulfilled during free-living and the further away an individual is from being in the real resting state, the larger the error.

The mean absolute percent error for the semi-structured activities in the study by Bhammar et al (Bhammar, Sawyer 2016) improved from 50% to 39% with SW5.2, compared to from 25% to 20% in the present study. Their study included more activities that may have influenced measurement error. In both studies there was little improvement in the bias for basketball playing, which demonstrated among the largest underestimations of the activities included, although the magnitude of error was more than double than in the present study. Further, although an improvement in the bias for biking was demonstrated only in the present study, the magnitude of the error with SW5.2 was similar between the studies, about 20-30 %. However, biking also demonstrated a proportional bias in the present study in line with what was observed in the study by Koehler et al with SW2.2 (Koehler, Braun 2011). As the participants in the present study performed biking at a self-selected speed, large variation in speed and error occurred.

The studies by Lee et al in 7-13 years old children (Lee, Kim 2016) and van Loo et al in 5-12 years old children (van Loo, Okely 2016) showed a reduction in the bias from SW2.2 to SW5.2, especially for biking, but there was still a general underestimation of energy expenditure, similar to the results in the present study. The mean absolute percent error in these studies improved from 31% to 15% and from 44% to 30%, respectively. In the present study, the corresponding changes were from 37% to 24% in 9-12 years old children and from 26% to 23% in 13-16 years old adolescents. Further, van Loo et al (van Loo, Okely 2016) observed similar proportional bias related to energy expenditure level with SW5.2 as in the present study, which was not seen in the study by Lee et al (Lee, Kim 2016). It is possible that the moderate and vigorous activities in the study by van Loo et al (van Loo, Okely 2016) were performed at a higher intensity. The present study confirmed the study by Lee et al (Lee, Kim 2016) concerning the large improvement in the bias of biking. In their study the mean absolute percent error changed from more than 50% down to about 10% depending on the intensity of biking. However, this improvement did not to occur so much at the individual level. The energy expenditure, and consequently the error, seemed to be reduced by the same factor in all participants in the present study. Both previous studies demonstrated an improvement in the estimation accuracy with SW5.2 for basketball (Lee, Kim 2016; van Loo, Okely 2016), as in the present study. The improvement was more apparent during moments of full-body movements like during dribbling compared to shooting involving only arm-movements (Lee, Kim 2016). Altogether, the magnitude of the errors for SW5.2 was very similar to what could be observed for the ActiGraph. However, because of the low accuracy of the waist-worn ActiGraph for biking, SW5.2 would be preferable to estimate energy expenditure in children and adolescents.

It was demonstrated in the present study that due to the larger improvements in the children, the overall accuracy of SW5.2 would be more comparable between the children, adolescents and adults. The mean absolute percent error of SW5.2 in the adults in the present study and in the adults in the study by Bhammar et al (Bhammar, Sawyer 2016) were 20% and 39%, respectively. The corresponding values in children in the present study, the study by Lee et al (Lee, Kim 2016) and the study by van Loo et al (van Loo, Okely 2016) were 24%, 15% and 30%, respectively.

Of great concerns are the large individual errors and the proportional bias of SenseWear observed in the present study and previous studies in children and adults, which are similar to what can be seen with the ActiGraph. For example, the individual MET-values during the ambulatory activities ranged from 2.5 during slow walking up to 15.0 during running and basket ball. The corresponding individual range in error was from ~30% overestimation during slow walking to ~20% underestimation during running and up to ~50% during basketball. These errors limit the use of SenseWear to compare groups with different physical activity levels, e.g. in a lifestyle behavior intervention study with one treatment group and one control, and to investigate the relationship between physical activity or energy expenditure level and different health parameters. As a calculation example, based on the results in children presented in Figure 3 and the mean body weight of 39 kg in this age-group, the ”true” total energy expenditure during the 40 minutes protocol for the child with the lowest energy expenditure level would be 546 kJ (14 $kJ \cdot kg^{-1}$ x 39kg) and for the child with the highest energy expenditure level 780 kJ (20 $kJ \cdot kg^{-1}$ x 39kg). However, in the first child the measurement error was 0 kJ, while energy expenditure was underestimated by 234 kJ in the second child. The consequence would be that the estimated energy expenditure in these two children would be the same, namely 546 kJ.

Strengths and limitations

The activities included were performed in their natural environment with few restrictions of the preconditions of participation and of the actual performance. They represent activities/movement commonly performed by the populations sampled. This design allowed us to mimic free-living and to capture the intra-individual and inter-individual sources of errors. Further, the accuracy of SenseWear was directly compared between different age-groups for similar types of activities and to a commonly used alternative method. The sample was relatively balanced concerning gender.

Still, the number of activities was limited. The ActiGraph algorithm by Santos-Lozano et al (Santos-Lozano, Santín-Medeiros 2013) did not include young children. It is possible that the measurement errors in this age-group would have been smaller in the present study with the correct algorithm available.

Conclusions

There were improvements in the measurement errors of SenseWear Armband with the updated algorithms. The largest improvement occurred in children and for biking. The new SenseWear algorithms increased comparability in accuracy between children, adolescents and adults. Although SenseWear is more accurate for the estimation of energy expenditure of biking than the waist-worn ActiGraph, these methods share measurement errors requiring further improvements for valid measures of physical activity and energy expenditure in clinical and epidemiological research. These errors include a proportional bias related to the energy expenditure level, in addition to the large individual errors.

Perspective

Clinical and epidemiological research investigating the importance of physical to health depend on accurate measures both at group level and individual level. The present study demonstrates important remaining limitations even with more sophisticated methods like SenseWear. Proprietary algorithms is a common feature among activity monitors, which limits the understanding of whether findings are true observations or consequences of measurement errors. Greater advancement in measurement accuracy is wanted for the progression of the physical activity research field, offering more open-source solutions that facilitates contributions by researchers (Sievänen & Kujala 2017).

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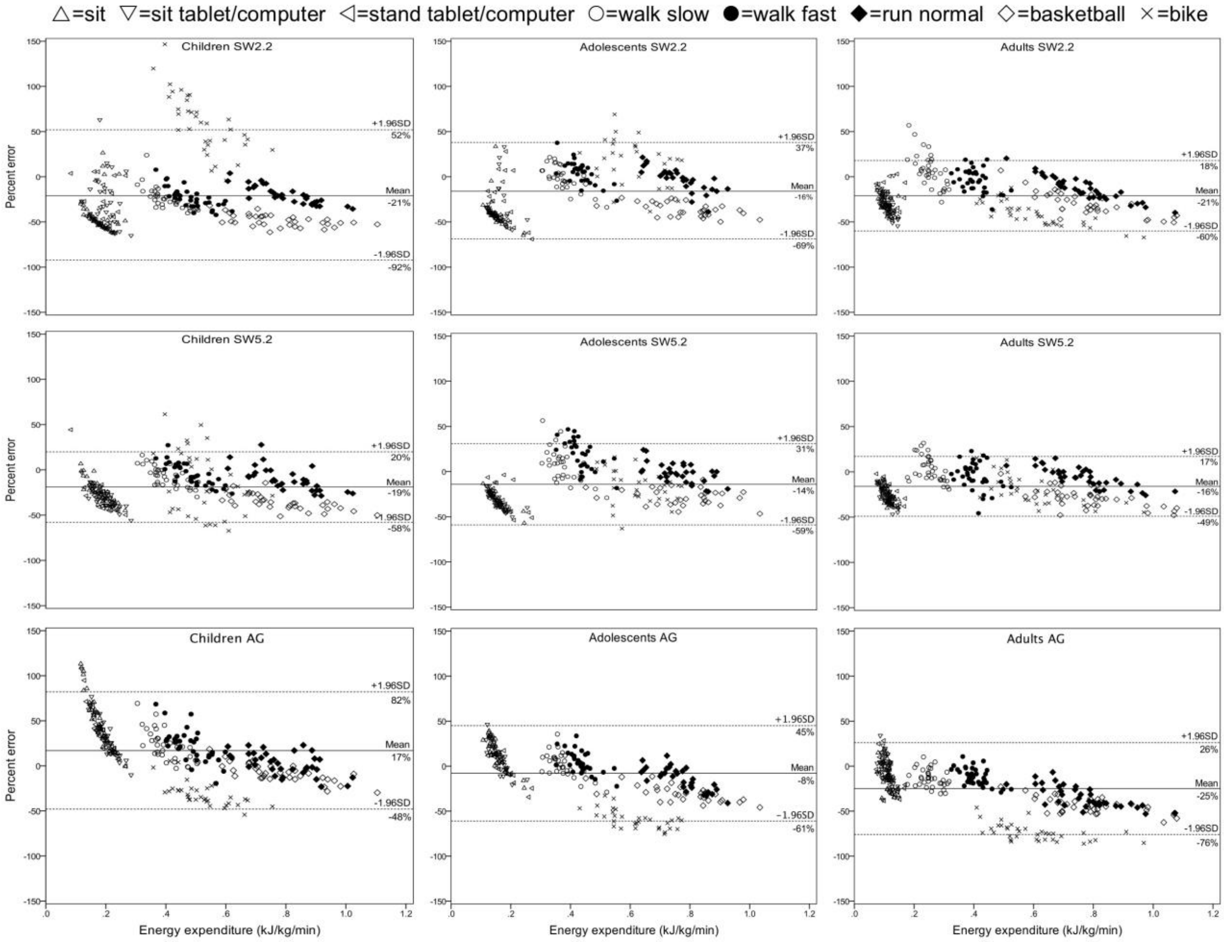
Figures

Figure 1. Bland-Altman plots of the individual percent errors (%) of all activities included for the Sensewear algorithm 2.2 (SW2.2) and 5.2 (SW5.2) and for the ActiGraph method (AG). Horizontal lines represent overall mean error and limits of agreement.



MET-value Mean	Sit	Sit tablet/ computer	Stand tablet/ computer	Walk slow	Walk fast	Run normal	Basket ball	Bike
Children	1.4	1.6	1.6	3.3	4.0	6.6	6.4	4.3
Adolescents	1.6	1.7	1.8	4.0	4.6	8.2	8.2	6.6
Adults	1.5	1.5	1.6	3.5	5.6	10.5	10.8	8.3

Figure 2. Mean absolute percent error and mean percent error (underestimation or overestimation) of estimated energy expenditure. Horizonal lines for mean absolute precent error represent mean of all activities; dotted line=SW2.2, dashed line=SW5.2, continuous line=AG. Total represent the error over the entire 40 minutes protocol.

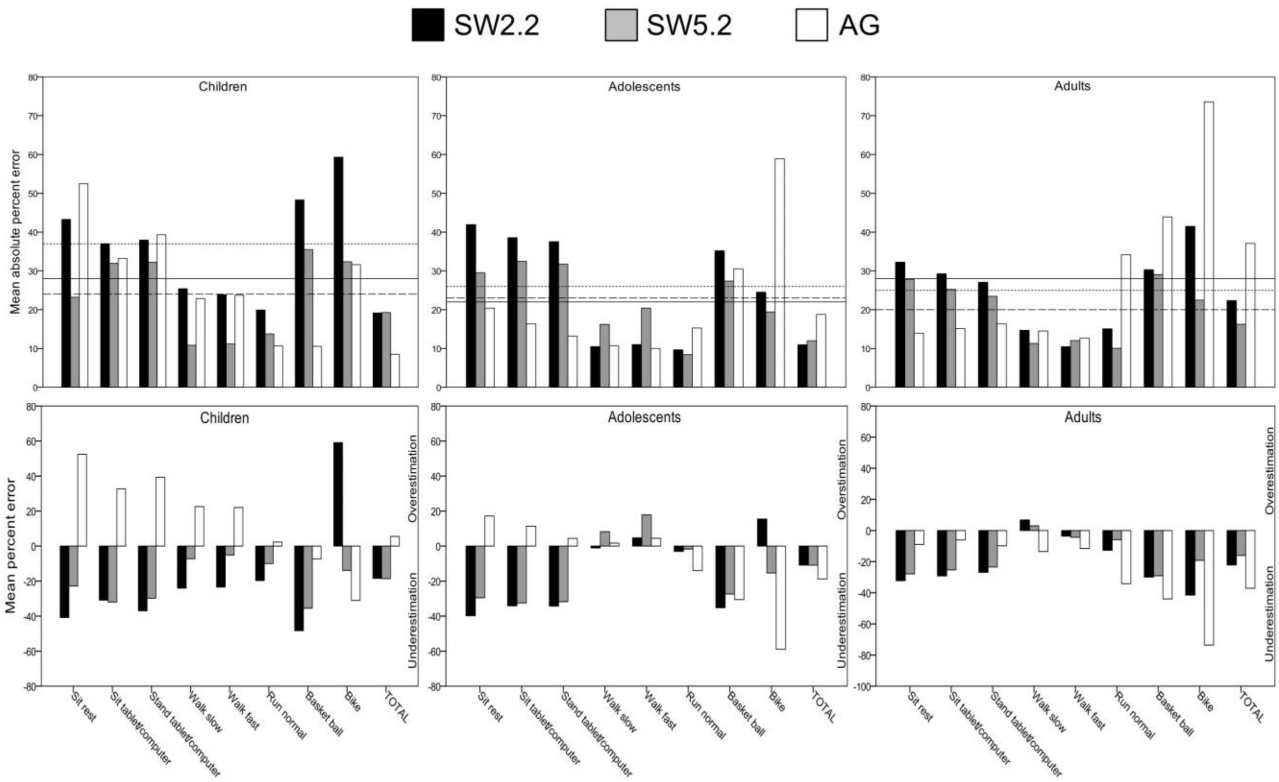


Figure 3. Bland-Altman plots including the entire 40 minutes protocol, with the energy expenditure level by indirect calorimetry on the x-axis and overall measurement error ($kJ \cdot kg^{-1}$) on the y-axis. Horizontal lines are the mean error and limits of agreement. The relationship between the energy expenditure level and the measurement error is presented with the regression line.