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Validity of combining heart rate and uniaxial acceleration to measure free-living physical activity energy expenditure in young men

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Villars C, Bergouignan A, Dugas J, Antoun E, Schoeller DA, Roth H, Maingon AC, Lefai E, Blanc S, Simon C. Validity of combining heart rate and uniaxial acceleration to measure free-living physical activity energy expenditure in young men. *J Appl Physiol* 113: 1763–1771, 2012. First published September 27, 2012; doi:10.1152/japplphysiol.01413.2011.—Combining accelerometry (ACC) with heart rate (HR) monitoring is thought to improve activity energy expenditure (AEE) estimations compared with ACC alone to evaluate the validity of ACC and HR used alone or combined. The purpose of this study was to estimate AEE in free-living conditions compared with doubly labeled water (DLW). Ten-day free-living AEE was measured by a DLW protocol in 35 18- to 55-yr-old men (11 lean active; 12 lean sedentary; 12 overweight sedentary) wearing an Actiheart (combining ACC and HR) and a RT3 accelerometer. AEE was estimated using group or individual calibration of the HR/AEE relationship, based on an exercise-tolerance test. In a subset ($n = 21$), AEE changes (ΔAEE) were measured after 1 mo of detraining (active subjects) or an 8-wk training (sedentary subjects). Actiheart-combined ACC/HR estimates were more accurate than estimates from HR or ACC alone. Accuracy of the Actiheart group-calibrated ACC/HR estimates was modest [intraclass correlation coefficient (ICC) = 0.62], with no bias but high root mean square error (RMSE) and limits of agreement (LOA). The mean bias of the estimates was reduced by one-third, like RMSE and LOA, by individual calibration (ICC = 0.81). Contrasting with group-calibrated estimates, the Actiheart individual-calibrated ACC/HR estimates explained 40% of the variance of the DLW-ΔAEE (ICC = 0.63). This study supports a good level of agreement between the Actiheart ACC/HR estimates and DLW-measured AEE in lean and overweight men with varying fitness levels. Individual calibration of the HR/AEE relationship is necessary for AEE estimations at an individual level rather than at group scale and for ΔAEE evaluation.

exercise; body movement; heart rate; accelerometer; doubly labeled water

ALTHOUGH REGULAR PARTICIPATION in physical activity (PA) is recognized as essential for reducing the risk of many adverse chronic diseases, including type 2 diabetes, cardiovascular diseases, osteoporosis, and cancer, the nature of the relationship between PA energy expenditure (PAEE) and specific health conditions remains discussed for many end points (24). Until recently, epidemiological studies have mainly relied on self-reported PA, which provides a biased assessment of activity energy expenditure (AEE) with limited accuracy or precision (28). This is particularly true for activities of light intensity that are either routine or spontaneous and thus difficult to report accurately. Yet, the contribution of these activities to total daily energy expenditure is important, most notably, in less-active and overweight subjects (34). Objective tools able to measure free-living AEE accurately and precisely, even at the low end of the volume and intensity-PA spectrum, are needed. Such easy-to-use instruments are essential to better investigate the dose-response relationship of PA with specific health benefits in large cohorts, in field research, or in clinical trials. They are also needed for the screening of sedentary lifestyles and prevention or management of chronic diseases in individuals.

Combined with indirect calorimetry measures of resting metabolic rate (RMR), doubly labeled water (DLW) provides an accurate method for measuring free-living AEE over a 10- to 14-day period. However, it requires a specific expertise and is expensive and inconvenient when used in large populations or in an individual-centered therapeutic perspective. Accelerometry (ACC) represents a more pragmatic and economically feasible alternative. However, recent reviews indicate that accuracy of current commercially available ACC to estimate AEE in free-living conditions is limited, at least when one single unit is used (8, 22). It was suggested that a combination of ACC with synchronized recording of heart rate (HR) and the use of different weighted equations (10, 14, 18, 32), as implemented in the Actiheart software (CamNtech, Cambridge, UK), may improve the validity and the accuracy of AEE estimation and be less dependent on individual calibration than HR recording used alone (11). The validity of Actiheart, the only commercially available device combining ACC and HR recordings, has mainly been evaluated in comparison with indirect calorimetry in laboratory- and in field-setting studies (2, 9, 14, 15, 33). Only one published study, conducted in Cameroon, has tested the validity of Actiheart-combined ACC/HR AEE estimates against DLW in free-living conditions and found no significant mean bias between AEE estimated from the combined sensor or measured by DLW (1). The validity of Actiheart to estimate changes in free-living PA over time or in response to an intervention has not been evaluated. Therefore, the purpose of this study was to validate the Actiheart-combined ACC/HR estimation using a DLW reference method as criterion in free-living adults with varying weight and fitness statuses. We used data from the lipid oxidation

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(LIPOX) study, which included lean active, and lean or overweight sedentary men to *1*) evaluate the validity of the Actiheart-combined ACC/HR estimates in free-living conditions and after an intervention on PA, *2*) compare the validity of these combined estimates with the validity of estimates based on Actiheart HR and ACC recording used alone and with the validity of the RT3 triaxial ACC estimates (Stayhealthy, Monrovia, CA), and *3*) evaluate if individual calibration of the HR relationship with AEE is needed to obtain an accurate estimation of AEE and AEE changes (ΔAEE).

Glossary

ACC	Accelerometry
AEE	Activity energy expenditure
BMI	Body mass index
DLW	Doubly labeled water
FM	Fat mass
HR	Heart rate
ICC	Intraclass correlation coefficient
LOA	Limits of agreement
PA	Physical activity
RMR	Resting metabolic rest
RMSE	Root mean square error
TBW	Total body water
TEE	Total energy expenditure

MATERIALS AND METHODS

Subjects and study design. This is a substudy within the LIPOX study that took place at the University Hospital of Strasbourg (France) and investigated the effect of a PA intervention on dietary lipid partitioning (unpublished observations). Briefly, the three LIPOX study groups of 12 healthy male volunteers (lean active, lean sedentary, and overweight sedentary men), aged 18–55 yr, recruited by flyers and advertisements in enterprise newsletters, were also instructed to wear an Actiheart and a RT3 triaxial accelerometer. Inclusion criteria were a BMI <25 kg/m^2 for lean subjects and a BMI ≥ 25 and <35 kg/m^2 for overweight subjects. Sedentary or active status was defined using the Monica Optional Study of PA (MOSPA) questionnaire (23), with sedentary subjects reporting sedentary occupations and no regular PA during leisure time and active subjects reporting at least 2–3 h/wk of moderate to vigorous leisure PA. The intervention consisted of a 1-mo voluntary reduction in structured and spontaneous PA in active subjects and an 8-wk aerobic program based on three supervised ergometer sessions at 50% of peak oxygen consumption (VO_2 peak) and one weekend self-directed aerobic session/wk for the sedentary subjects. Throughout the intervention, the diet was adjusted regularly by a dietician to maintain energy balance. Before and at the end of the PA intervention, participants underwent two series of similar clinical tests. An incremental exercise-tolerance test (16) was performed on an electronically braked cycle ergometer (1000S, Medifit, Belgium) to determine VO_2 peak. These tests were also used to individually calibrate the relationship between HR and AEE, using a quadratic regression and assuming an energetic value of oxygen of 20.35 kJ/l. AEE was measured using a 10-day DLW protocol combined with indirect calorimetry measurements of RMR. At *day 1* of the DLW protocol, participants were equipped with the Actiheart device (CamNtech) and with a RT3 triaxial accelerometer (Stayhealthy). They were instructed to wear them 24 h/day, at least for the first 7 days of the DLW protocol. They were given a log to record when they wore the monitors and their sleep time. The study protocol was approved by the Alsace I Institutional Review Board (France), and all subjects provided written, informed consent before study initiation.

Because of too noisy Actiheart data for inferring latent HR (see MATERIALS AND METHODS) in one subject, data of 35 subjects (11 lean active, 12 lean sedentary, and 12 overweight sedentary subjects) were available for the comparisons of baseline free-living Actiheart- or RT3-AEE estimates with the DLW criterion measures. Baseline and postintervention DLW, RT3, and Actiheart data, available for 21 subjects (six lean active, eight lean sedentary, and seven overweight sedentary subjects), were used to compare the Actiheart and RT3 estimates of intraindividual ΔAEE with the DLW-ΔAEE criterion measures. Follow-up data were missing for 14 subjects: drop-out of the study ($n = 1$), fever during the postintervention DLW test ($n = 1$), refusal to wear the Actiheart device for a second time ($n = 2$), allergic skin reaction ($n = 3$), missing postexercise-tolerance test ($n = 1$), missing or inconsistencies in isotope data in DLW measure ($n = 3$), and too noisy Actiheart data ($n = 3$).

RMR- and DLW-based criterion AEE determination. RMR was measured via indirect calorimetry using a Deltatrac-ventilated open-hood metabolic cart (Deltatrac II, GE Healthcare Clinical Systems, Waukesha, WI). Before each test, the gas analyzers were calibrated with a reference gas mixture (95.0% O_2 and 5.0% CO_2). Regularly, methanol burns were conducted to check volume and analyzer's accuracy. Measurements took place between 6 AM and 7 AM after a 12-h overnight fast with subjects refraining from exercise for at least 12 h. Subjects rested in a supine position in a thermal-regulated environment for at least 30 min before the 60-min respiratory gas-collection period. The 60-min data were examined individually, and only plateaued data were kept for RMR calculations that were performed using the modified Weir equation (13, 37).

Free-living TEE was determined using a 10-day DLW protocol (3, 26). After providing a baseline urine sample, subjects ingested a premixed dose of 2 g/kg TBW. The dose was composed of 0.2 g/kg TBW $H_2{}^{18}O$ (10% enriched) and 0.15 g/kg TBW ^2H_2O (99% enriched; Cambridge Isotope Laboratories, Andover, MA). Equilibration was assessed in urine samples collected at 3 h and 4 h postdose. Three subsequent urine samples were collected on *days 3*, *7*, and *10* of the protocol. Equilibration and end-point urine samples were cleaned as described previously (3). $^2H_2$ and ^{18}O isotopic enrichment was analyzed by pyrolysis on an elemental analyzer (Flash HT, ThermoFisher Scientific, Waltham, MA) interfaced with an isotope ratio mass spectrometry (Delta V, ThermoFisher Scientific). Analyses were performed in quadruplicate and repeated if the SD exceeded 2% for ^2H and 0.5% for ^{18}O. TBW and TEE were calculated as described previously using a food quotient of 0.86 (4, 5), with the slight change that the constant elimination rates from both $^2H_2$ and ^{18}O were calculated with a multipoint method. DLW-AEE was calculated as 0.9 TEE − RMR. Since the average ratio of mean sleep metabolic rate/RMR has been found to be approximately one (38), RMR was used for both waking and sleeping time. Fat-free mass was calculated from TBW using a hydration factor of 0.73 (35), and FM was calculated from the difference of body mass.

Free-living RT3- and Actiheart-AEE estimates. On *day 1* of the DLW protocol, subjects were equipped with the RT3 accelerometer worn laterally at the waistline in nylon pouches, secured laterally with an elastic belt. The Actiheart-combined sensor was positioned horizontally on the chest at the level of the third intercostal space using hypoallergenic electrodes (3M Red Dot electrodes, 3M France, 95006 Cergy-Pontoise Cedex, France). Free-living HR and ACC were measured in 1-min epochs, concurrently with the DLW measurement. The participants were requested to carry on with their habitual lifestyle while wearing the monitor at all times. The monitors were to be taken off only during showering, bathing, or water activities, and subjects were asked to limit water sports. At the end of the DLW protocol, data from the RT3 and Actiheart monitors were downloaded into a database using the commercial software. The Actiheart software was used to clean and recover or interpolate noisy and missing HR data (for gaps <5 min) using the manufacturer's built-in algorithm (http://www.camntech.com, CamNtech). Briefly, HR <30 beats/min or HR associated to a high

rate of change is considered missing. Algorithms based on minute-by-minute minimum and maximum interbeat intervals and linear interpolations are used to recover missing value gaps <5 min. The activity logs were examined for consistency of reported wear time with the monitors' recordings. No substantial discrepancies were found by the investigators.

The triaxial minute-by-minute RT3 counts were converted into minute-by-minute AEE using the RT3 software (unpublished proprietary equations).

Actiheart counts and HR data were first used to estimate separate acceleration and flex-HR models. The Actiheart counts were converted to ACC-AEE estimates using group-calibrated ACC equations derived from walking and running accelerations in studies conducted with the Actiheart (12). Flex-HR was estimated with a sleeping HR-based regression equation (10). Flex-HR AEE estimates were calculated using the individual-calibrated HR/AEE relationships above the flex-HR and were set up to 0 for minutes below that point.

In a second step, minute-by-minute HR- and ACC-AEE estimates were combined in a branched equations model as described previously (12) and as proposed by the Actiheart software to calculate daily AEE. In the branched equations model, the relative contribution of activity and HR to the calculation of AEE is weighted epoch by epoch according to different counts and HR thresholds (12). Essentially, when both ACC and HR values are low, the ACC-AEE estimates have more weight, whereas when ACC and HR values are high, the HR-AEE estimates are the predominant contributor to the minute-by-minute AEE estimates. To minimize the influence of HR increase not related to PA, the normal HR data weighting was reduced where there was a raised HR in the absence of sufficient counts ("stress option" of the Actiheart software). Two different branched models were estimated. The first one (Actiheart group-calibrated ACC/HR-AEE) used group-calibrated equations for both the activity and AEE estimates combined in the model (12). To assess the additional benefit of using individual calibration compared with group calibration, a second model was based on the same group-calibrated ACC-AEE estimates but in combination with individual-calibrated HR-AEE estimates (Actiheart individual-calibrated ACC/HR-AEE). Additional combined ACC/HR-AEE models were estimated without the stress option or using different equations published previously, obtained with the Actiheart device in different populations (10, 15). Since their agreement with criterion measures was similar or lower than the agreement of the first two models, only these latter are presented.

For each of the models, minute-by-minute AEE estimates were summed over 24 h to give daily free-living AEE estimates. To limit the impact of missing values and nonwear periods on the results, minute-by-minute AEE missing values were replaced either by the awake minute-by-minute mean AEE estimates of the same day or by zero for sleeping time (as determined from the record diary); individuals who did not have at least 3 valid days (defined as >10 h or >80% of the awake time) were excluded (36). Finally, a maximum of 7 valid days recorded during each DLW protocol was retained for each subject.

Statistics. Descriptive characteristics of the study sample are presented as means with SD and stratified by overweight status and PA groups. ANOVA was used to assess differences in the descriptive variables among groups.

Agreement between daily Actiheart- or RT3-AEE and ΔAEE estimates with daily DLW-AEE and DLW-ΔAEE criterion measures was assessed in different ways. Unadjusted Pearson coefficients were computed to assess the degree to which the AEE models explained the variance in the criterion measure. Estimation error was quantified by the RMSE between the estimates and the criterion measures (lower RMSE indicates a higher level of estimation accuracy). ICCs were calculated. ICCs are thought to be more suitable reliability parameters than the classical, widely used Pearson correlation coefficients, as the latter cannot detect either constant or proportional bias and ignores the inaccuracy component (20). Criterion validity of the different monitoring models against DLW-AEE was analyzed further using the Bland-Altman agreement method (6). The mean bias and the 95% LOA between the estimates and the criterion are presented. The associations of absolute errors with the reference DLW-AEE measures and with different characteristics of the subjects as potential explanatory variables were examined using linear regression models.

For all models, AEE estimates and criterion measures were expressed in $kJ \cdot kg^{-1} \cdot day^{-1}$, as this is regarded to be preferable from a biological perspective, specifically when subjects have various body sizes (25, 27). However, given the lack of agreement on the most appropriate way to adjust for the contribution of body weight to energy expenditure (22, 27), we additionally examined the residuals of AEE regressed on body weight and calculated models with AEE expressed in MJ/day. Since these different methods produced similar results, we present only the data using AEE expressed in $kJ \cdot kg^{-1} \cdot day^{-1}$. Statistical analyses were carried out using SAS V9.2 (SAS Institute, Cary, NC), with an α level set at 0.05.

RESULTS

Baseline characteristics. Table 1 presents baseline characteristics of the subjects. In line with our a priori inclusion criteria, BMI was higher in the overweight group than in the lean groups ($P < 0.001$) with a lower FM in lean active subjects compared with both lean sedentary ($P < 0.01$) and overweight sedentary subjects ($P < 0.001$). DLW-AEE, expressed by body weight, was higher in active subjects than in sedentary ones, as was VO_2 peak ($P < 0.01$ for lean sedentary subjects, and $P < 0.001$ for overweight ones). DLW-AEE was almost twice as high in active subjects then in lean sedentary

Table 1. *Baseline characteristics of the subjects (means ± SD)*

	All $n = 35$	Lean Active $n = 11$	Lean Sedentary $n = 12$	Overweight Sedentary $n = 12$
Age (yr)	27.6 ± 6.5	24.3 ± 4.0	28.4 ± 8.4	29.9 ± 5.4
Weight (kg)	82.3 ± 14.4	72.1 ± 7.6	76.0 ± 9.0	97.8 ± 9.8*,†
BMI (kg/m^2)	25.2 ± 4.0	22.5 ± 1.5	22.8 ± 2.0	30.1 ± 1.7*,†
FM (%)	23.7 ± 8.1	15.1 ± 4.4	23.4 ± 5.3‡	31.8 ± 3.6*,†
VO_2 peak ($ml \cdot kg^{-1} \cdot min^{-1}$)	56.0 ± 16.5	72.7 ± 14.1	53.0 ± 9.8‡	43.7 ± 10.7*,§
TEE (MJ/day)	12.8 ± 2.2	13.8 ± 1.7	11.0 ± 1.6‡	13.6 ± 2.2¶
REE ($kJ \cdot ^{kg^{-1}} \cdot day^{-1}$)	58.3 ± 5.6	61.4 ± 3.7	60.6 ± 5.9	53.2 ± 3.3*,§
AEE ($kJ \cdot kg^{-1} \cdot day^{-1}$)	58.1 ± 23.7	84.5 ± 18.9	44.1 ± 16.2*	47.8 ± 10.8*
Valid days (*n*)	6.7 ± 0.8	6.4 ± 1.3	6.8 ± 0.5	6.8 ± 0.6
HR-sleep (beats/min)	52.1 ± 5.9	47.2 ± 5.3	53.8 ± 4.5	55.1 ± 5.0

VO_2 peak, peak oxygen consumption; REE, resting energy expenditure. Significantly different from lean active subjects: *$P < 0.001$; ‡$P < 0.01$. Significantly different from lean sedentary subjects: †$P < 0.001$; §$P < 0.05$; ¶$P < 0.01$.

and overweight subjects. As reported by the MOSPA, the majority of the subjects was engaged in sedentary work occupations, regardless of the stratification group. Sedentary subjects engaged in more television/video and computer time ($P < 0.001$). Other baseline variables, including sleep HR, did not differ among groups.

A mean of 6.7 ± 0.8 daily recordings/subject was included in the analyses. A total of 6.7 ± 5.9% of the HR minute-to-minute data was lost during recording but could be interpolated or recovered by the built-in Actiheart software. Only 2.1 ± 1.9% of the minute-to-minute awake-time data was set to invalid or missing and could not be recovered. Thus 28 out of the 35 subjects used in the analyses had six or more valid baseline 24-h recordings.

Validity of different AEE estimates in free-living baseline conditions. ICC and correlations between DLW-AEE and AEE estimates obtained from Actiheart and RT3 are presented in Table 2 for the whole sample of subjects. The AEE estimates from group-calibrated flex-HR models barely explained 13% of the total variance in DLW criterion measure (ICC = 0.27), with a systematic overestimation, an important RMSE, and a proportional bias ($P < 0.001$; data not shown). The accuracy of the flex-HR AEE estimates was improved by individual calibration of the relationship between HR and AEE, as indicated by an ICC of 0.52, with, however, an overestimation and a RMSE still remaining high (32.2 ± 29.6 and 43.5 $kJ \cdot kg^{-1} \cdot day^{-1}$, respectively). The accuracy of AEE estimates obtained from both RT3 and Actiheart ACC used alone was similar (ICC of 0.40 and 0.47, respectively), with both models presenting a systematic underestimation and a proportional bias ($P < 0.001$; data not shown).

Combining Actiheart ACC with HR (Table 2 and Fig. 1, *A* and *B*) improved the accuracy of the models, as compared with estimates from HR or ACC alone. The Actiheart group-calibrated ACC/HR-combined model showed a modest agreement with DLW-AEE, as indicated by an ICC of 0.62. As illustrated by the Bland-Altman plot, there was a slight systematic bias between the group-calibrated estimates and DLW-AEE (-7.6 ± 20.2 $kJ \cdot kg^{-1} \cdot day^{-1}$; $P < 0.05$). The estimates' errors were not correlated significantly with the DLW criterion measure ($P = 0.71$). However, RMSE and LOA were wide (21.3 $kJ \cdot kg^{-1} \cdot day^{-1}$ and ~40 $kJ \cdot kg^{-1} \cdot day^{-1}$, respectively).

Individual calibration of the HR relationship with AEE using the exercise-tolerance test further improved the AEE estimation (Table 2 and Fig. 1, *A* and *C*) with a fairly good accuracy (ICC = 0.81). The Actiheart individual-calibrated estimates accounted for 70% of the total variance with no significant systematic bias. Compared with the Actiheart group-calibrated model, the mean bias of the estimates, RMSE and LOA, was reduced by one-third (-4.6 ± 13.1 $kJ \cdot kg^{-1} \cdot day^{-1}$; 13.7 $kJ \cdot kg^{-1} \cdot day^{-1}$; and ~25 $kJ \cdot kg^{-1} \cdot day^{-1}$, respectively). As for the Actiheart group-calibrated model, the AEE residual errors were not related significantly with VO_2 peak, sleep HR, or any of the anthropometric measures (data not shown), but there was a slight, significant negative proportional bias ($P < 0.01$; Fig. 1*C*).

ICC and correlations between DLW criterion measures and RT3 ACC or Actiheart ACC/HR estimates stratified according to the BMI and PA inclusion groups are detailed in Table 3. The accuracy of RT3 ACC estimates was lower in overweight subjects than in lean subjects. Concerning the Actiheart group-calibrated combined model, the correlations and the accuracy of the estimates were higher for the lean sedentary subjects than for the lean active and overweight sedentary subjects (ICC of 0.52, 0.22, and 0.30, respectively). Individual calibration of the HR relationship with AEE improved the validity of the Actiheart-combined model in all three groups, although the reliability remained lower in overweight sedentary subjects [ICC = 0.46, as compared with lean active subjects (ICC = 0.85) and with lean sedentary ones (ICC = 0.73)].

Validity of Actiheart for estimating intervention-induced ΔAEE. ICC and correlations between DLW-ΔAEE induced by the intervention and the RT3- and Actiheart-ΔAEE estimates are presented in Table 4 for the 21 subjects, for which both pre- and postintervention valid recordings were available.

The correlations of RT3 and Actiheart group-calibrated ACC/HR ΔAEE estimates with DLW-ΔAEE were low, as were the correlations and the accuracies of the predictions (ICC of 0.28 and 0.11 and RMSE of 16.0 and 30.2 $kJ \cdot kg^{-1} \cdot day^{-1}$, respectively).

Individual calibration of the HR relationship with AEE improved the ΔAEE prediction from Actiheart ACC/HR combined model (Table 4 and Fig. 2) with a modest accuracy (ICC = 0.63). The estimates explained 40% of the variance of the DLW-ΔAEE. However, Bland-Altman plots showed a significant bias between the estimates and the criterion ΔAEE (6.3 ± 11.7 $kJ \cdot kg^{-1} \cdot day^{-1}$; $P = 0.03$), and RMSE (13.0 $kJ \cdot kg^{-1} \cdot day^{-1}$) and LOA (23.3 $kJ \cdot kg^{-1} \cdot day^{-1}$) were quite high. The improvement of the predictions using individual calibration was particularly noticeable in the active-detrained subjects. The accuracy of the Actiheart models based on the individual calibration obtained from the first exercise-tolerance test applied to both pre-and postintervention data was low (13% of the DLW-AEE explained; ICC = 0.37).

Table 2. *Comparison between DLW-measured AEE and the different estimates obtained using Actiheart or RT3 (n = 35)*

Models*	AEE Estimate† ($kJ \cdot kg^{-1} \cdot day^{-1}$)	Correlation (r^2)	ICC	RMSE ($kJ \cdot kg^{-1} \cdot day^{-1}$)	Bias†,‡ ($kJ \cdot kg^{-1} \cdot day^{-1}$)	95% LOA ($kJ \cdot kg^{-1} \cdot day^{-1}$)
Group-calibrated flex-HR	91.3 [51.9]	0.13	0.27	58.4	33.2 [48.7]	−64.2; 130.6
Individual-calibrated flex-HR	90.3 [35.4]	0.31	0.52	43.5	32.2 [29.6]	−27.1; 91.4
RT3 ACC	39.7 [13.3]	0.22	0.40	28.2	−19.1 [21.0]	−61.1; 22.9
Actiheart group-calibrated ACC	30.8 [11.0]	0.38	0.47	33.1	−27.3 [19.0]	−65.2; 10.6
Actiheart group-calibrated ACC/HR	50.5 [22.5]	0.38	0.62	21.3	−7.6 [20.2]	−47.9; 32.7
Actiheart individual-calibrated ACC/HR	53.5 [18.5]	0.70	0.81	13.7	−4.6 [13.1]	−30.8; 21.6

*Models of AEE prediction: Group-calibrated flex-HR, flex-HR model with group calibration; Individual-calibrated flex-HR, flex-HR model with individual calibration; Actiheart group-calibrated ACC/HR, Actiheart-combined HR recording with group calibration and ACC; Actiheart individual-calibrated ACC/HR, Actiheart-combined HR recording with individual calibration and ACC. †Values are presented as means [SD]. ‡Mean bias = predicted − criterion. Mean DLW-measured AEE was 58.1 ± 23.7 $kJ \cdot kg^{-1} \cdot day^{-1}$.

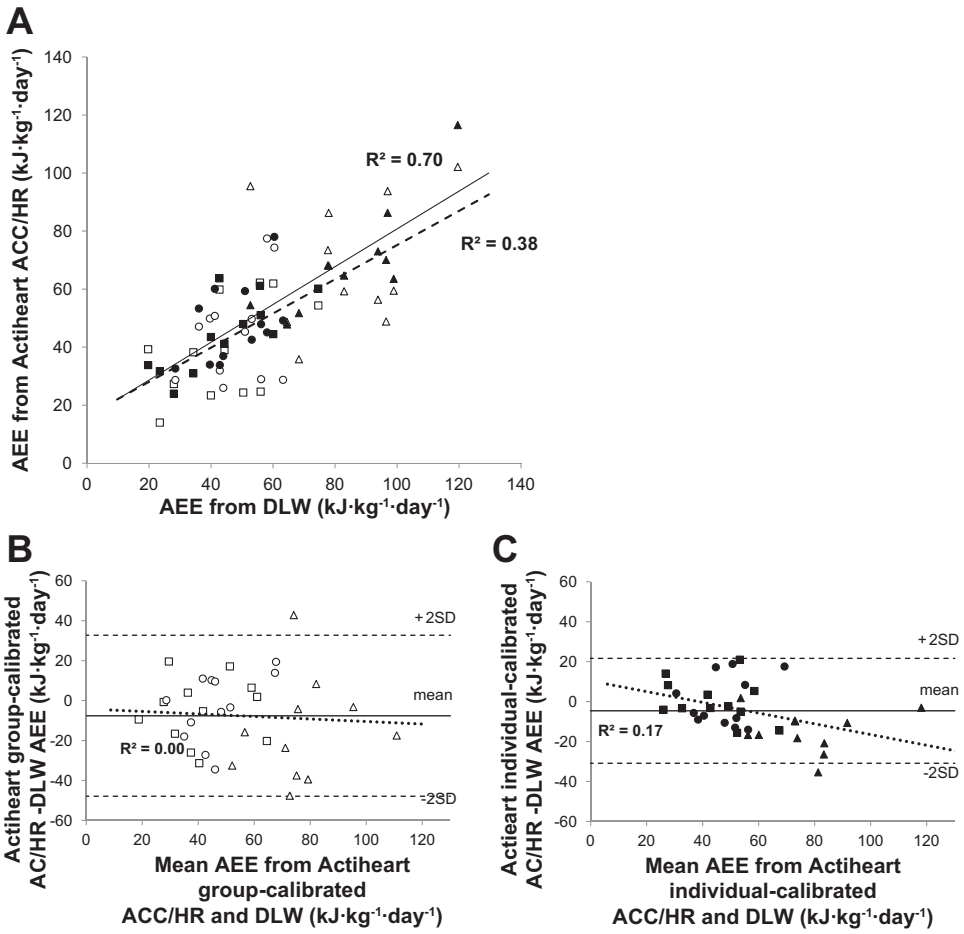

Fig. 1. Correlations of Actiheart group-calibrated and individual-calibrated ACC/HR AEE estimates with DLW-AEE criterion measures (*A*). Corresponding Bland-Altman plots: Actiheart group-calibrated ACC/HR AEE estimates (*B*) and Actiheart individual-calibrated ACC/HR AEE estimates (*C*). Data from 11 lean active, 12 lean sedentary, and 12 overweight sedentary subjects. Actiheart group-calibrated ACC/HR: △, lean active; ○, lean sedentary; □, overweight sedentary. Actiheart individual-calibrated ACC/HR: ▲, lean active; ●, lean sedentary; ■, overweight sedentary. Bland-Altman plots: solid lines show the mean difference between methods, and dotted lines show the LOA (±2 SD) of the mean difference.

It should be noted that cross-sectional correlations between the second set of AEE estimates and the corresponding DLW-AEE measures were lower than the correlations observed with the first set of data for all of the models. Explained variances for the first and second cross-sectional sets of data were, respectively, 40% and 21% for the Actiheart group-calibrated ACC/HR models and 72% and 38% for the Actiheart individual-calibrated ACC/HR models (data not shown).

DISCUSSION

In this study, we aimed to validate the Actiheart-combined ACC/HR AEE estimation against DLW criterion measure in healthy men with varying weight status and PA levels. Our results confirm that AEE estimates based on both recordings combined in a weighted, branched model correlate better with DLW reference measures in free-living conditions than esti-

Table 3. *Comparison between DLW-measured AEE and the different estimates obtained using Actiheart or RT3, according to BMI and PA stratification groups (11 lean active, 12 lean sedentary, and 12 overweight sedentary subjects)*

Models*	DLW AEE† (kJ·kg^{-1}·day^{-1})	AEE Estimate† (kJ·kg^{-1}·day^{-1})	Correlation (r^2)	ICC	RMSE (kJ·kg^{-1}·day^{-1})	Bias†,‡ (kJ·kg^{-1}·day^{-1})	95% LOA (kJ·kg^{-1}·day^{-1})
RT3 ACC							
Lean active	84.5 [18.9]	45.7 [16.0]	0.25	0.49	42.4	−38.9 [17.7]	−74.3; 3.5
Lean sedentary	44.1 [16.2]	34.6 [11.9]	0.30	0.50	17.1	−10.4 [14.2]	−38.8; 18.0
Overweight sedentary	47.8 [10.8]	38.9 [10.4]	0.06	<0.01	18.3	−9.0 [16.7]	−42.3; 24.4
Actiheart group-calibrated ACC/HR							
Lean active	84.5 [18.9]	69.1 [22.3]	0.05	0.22	29.1	−15.5 [25.9]	−67.2; 36.3
Lean sedentary	44.1 [16.2]	39.1 [17.0]	0.27	0.52	16.3	−5.0 [16.2]	−37.5; 31.3
Overweight sedentary	47.8 [10.8]	44.9 [17.4]	0.11	0.30	16.6	−2.9 [17.0]	−37.0; 31.2
Actiheart individual-calibrated ACC/HR							
Lean active	84.5 [18.9]	69.5 [18.9]	0.72	0.85	18.1	−15 [10.5]	−36.0; 5.9
Lean sedentary	44.1 [16.2]	44.5 [12.9]	0.57	0.73	10.3	0.4 [10.7]	−21.1; 21.8
Overweight sedentary	47.8 [10.8]	47.8 [13.5]	0.23	0.46	12.1	−0.1 [12.6]	−25.4; 25.2

*Models of AEE prediction. †Values are presented as means [SD]. ‡Mean bias = predicted − criterion.

Table 4. *Comparison between DLW-measured ΔAEE and the different estimates obtained using Actiheart for all subjects and according to PA levels (6 lean active and 15 lean or overweight sedentary subjects)*

Models*	DLW ΔAEE† (kJ·kg^{-1}·day^{-1})	ΔAEE Estimate† (kJ·kg^{-1}·day^{-1})	Correlation (r^2)	ICC	RMSE (kJ·kg^{-1}·day^{-1})	Bias†,‡ (kJ·kg^{-1}·day^{-1})	95% LOA (kJ·kg^{-1}·day^{-1})
RT3 ACC							
All subjects	−2.9 [13.3]	6.2 [13.6]	0.10	0.28	16.0	3.9 [16.0]	−28.0; 35.9
Lean active	−7.4 [13.3]	−1.8 [5.7]		<0.01	17.8	5.6 [16.7]	−27.0; 39.0
Sedentary	8.1 [10.2]	11.3 [14.9]	0.05	0.14	17.7	2.9 [16.2]	−29.5; 35.3
Actiheart group-calibrated ACC/HR							
All subjects	3.4 [13.2]	17.6 [25.7]	0.02	0.11	30.2	14.3 [27.3]	−40.3; 68.9
Lean active	−8 [14.4]	7.2 [31.7]		<0.01	41.8	15.2 [42.7]	−70.2; 100.6
Sedentary	7.9 [9.9]	21.8 [22.8]	0.21	0.33	24.1	13.9 [20.3]	−26.7; 54.5
Actiheart individual-calibrated ACC/HR (using pre- and postintervention tests)							
All subjects	3.4 [13.2]	9.6 [14.0]	0.40	0.63	13.0	6.3 [11.7]	−17.1; 29.6
Lean active	−8.0 [14.4]	−0.8 [11.6]	0.39	0.61	12.7	7.2 [11.5]	−15.8; 30.2
Sedentary	7.9 [9.9]	13.8 [12.9]	0.21	0.44	13.1	5.9 [12.1]	−18.4; 30.2
Actiheart individual-calibrated ACC/HR (using preintervention tests twice)							
All subjects	3.4 [13.2]	13.1 [13.1]	0.13	0.37	17.5	9.7 [14.8]	−19.9; 39.4
Lean active	−8.0 [14.4]	9.4 [8.8]	0.00	<0.01	23.3	17.4 [17.0]	−16.6; 51.4
Sedentary	7.9 [9.9]	14.6 [14.5]	0.21	0.43	14.5	6.7 [13.3]	−19.9; 33.3

ΔAEE, AAE change. *Models of AEE prediction. †Values are presented as means [SD]. ‡Mean bias = predicted − criterion.

mates from HR or ACC alone. When using group-calibrated equations, the agreement of the mean estimates was modest, as indicated by an ICC of 0.62, although the wide LOA restrain their use for individual prediction. Individual calibration of the HR relationship with AEE, using an exercise-tolerance test, further improved the AEE prediction of the combined model that accounted for 70% of the total variance in DLW-AEE, with no significant bias and a reduction by one-third of RMSE and LOA, leading to good individual estimates of free-living AEE (ICC = 0.81). We additionally demonstrated that the

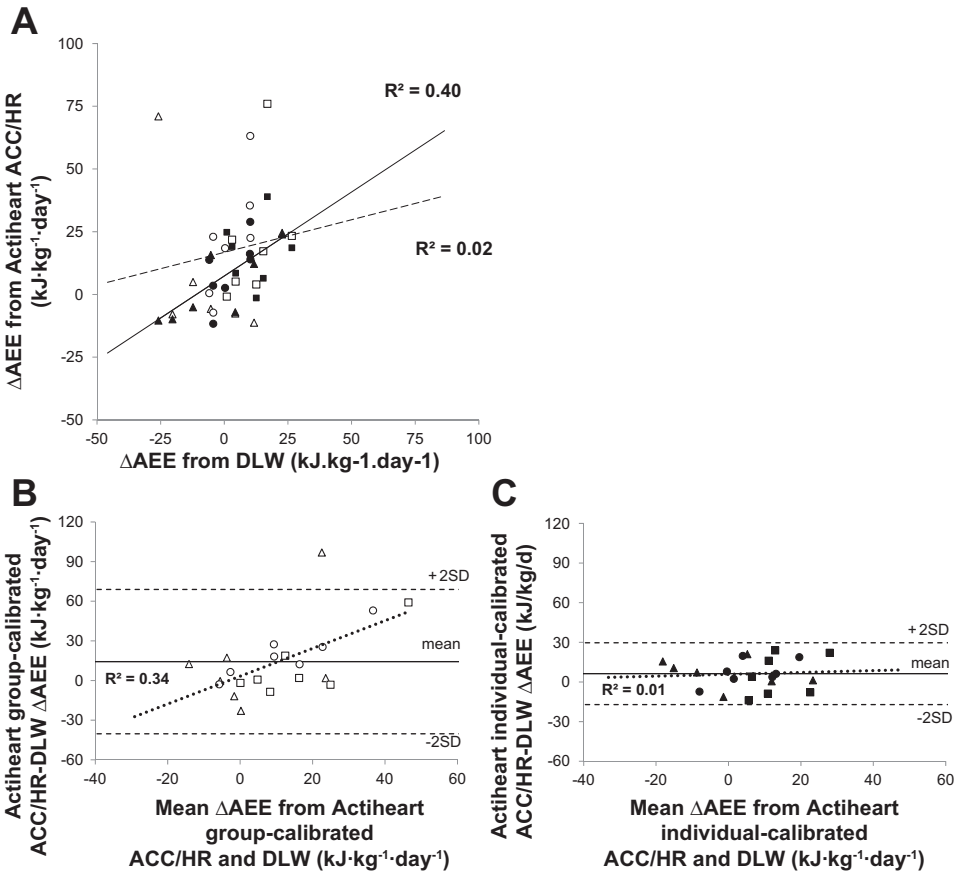

Fig. 2. Correlations of Actiheart group-calibrated ACC/HR and Actiheart individual-calibrated ACC/HR ΔAEE estimates with DLW-ΔAEE criterion measures (*A*). Corresponding Bland-Altman plots: Actiheart group-calibrated ACC/HR ΔAEE estimates (*B*) and Actiheart individual-calibrated ACC/HR ΔAEE estimates (*C*). Data from 6 lean active, 8 lean sedentary, and 7 overweight sedentary subjects. Actiheart group-calibrated ACC/HR: △, lean active; ○, lean sedentary; □, overweight sedentary. Actiheart individual-calibrated ACC/HR: ▲, lean active; ●, lean sedentary; ■, overweight sedentary. Bland-Altman plots: solid lines show the mean difference between methods, and dotted lines show the LOA (±2 SD) of the mean difference.

Actiheart-combined ACC/HR estimates based on individual but not on group calibration can be used to estimate changes induced by an intervention, at least at group level, with a modest agreement.

As reported previously (22), when used alone, the two accelerometers (i.e., the triaxial RT3 and the monoaxial sensor of the Actiheart) tended to underestimate free-living AEE. A proportional bias was observed with less accuracy to predict high-intensity activities, such as performed by our group of active subjects. In accordance with our results, a recent review reported that the accuracy of commercially available accelerometers in evaluating free-living AEE was generally modest with activity counts explaining <25% of DLW-AEE variance (22). This has been partly related to the nonuniqueness in the relationship between activity counts and the intraindividual variability in AEE and to a poor ability of accelerometers to detect nonambulatory or load-bearing activities (7). On the other hand, the main limitation when using HR alone is that it is affected by factors other than PA. Additionally, whereas HR and AEE are closely correlated during exercise, during sedentary and low-intensity activities, this relationship no longer holds. Different methods, such as the flex-HR method, have been proposed to overcome these limitations (30). However, there is no clear consensus of defining the flex-HR, which affects the accuracy of the estimates. As indicated by our results, even with such an approach, although the individual calibration improves the reliability of the estimates, HR recordings used alone had a reduced ability to predict individual free-living AEE at the individual level with a systematic overestimation of free-living AEE.

Combining HR monitoring with ACC compensates for the limitations of ACC by partially taking into account variance in energy cost of moderate to vigorous activities (18). The use of branched equation models giving a higher weight to the contribution of HR for activities of high intensity than for low-intensity activities was suggested to further improve the AEE estimates (11, 32). However, the Actiheart monitor, which is based on such an approach, was mainly validated against indirect calorimetry during standardized laboratory activities and in a field-setting study that does not really reflect activity patterns of daily life (2, 9, 15, 29, 33). In the present study conducted in free-living conditions, the precision and the accuracy of the Actiheart-combined model certainly exceeded those of estimates based on either ACC or HR used alone, at least when using a correction that minimizes the contribution of HR when not associated to ACC counts.

Our data extend the results of Assah et al. (1), who studied 33 rural and urban adults from sub-Saharan Africa, by providing data in a European population living in a more urbanized and mechanized environment and with a large range of BMI. With the use of group calibration, these authors reported a nonsignificant mean bias between AEE estimated from the combined sensor or measured by DLW with a RMSE (29.9 $kJ \cdot kg^{-1} \cdot day^{-1}$) and LOA similar to our results. However, they found that the combined sensor explained only 16% of the variance in DLW-measured AEE. Although the mean activity level of our subjects was similar to that of the sub-Saharan volunteers with an even greater AEE in our active subjects, the European urban environment of our subjects may have favored more acceleration-dependent and less weight-bearing activities, thus contributing to the better correlation observed in our study. Consistent with this hypothesis, Assah et al. (1) found that the Actiheart-AEE prediction was more accurate in urban compared with rural volunteers.

Both biomechanical modifications during walking and sensor-placement differences (with respect to center of mass of the body) are responsible for a loss of efficiency of waist accelerometers in overweight and obese subjects. Thus evaluation of AEE with ACC may be particularly challenging (8). The data obtained with the RT3 suggest that waist ACC has a poor accuracy to predict AEE at the individual level in overweight subjects, as reported previously (19). Moreover, our results suggest that group calibration of the HR relationship with AEE may be less appropriate in overweight than in lean sedentary subjects.

Individual calibration of the HR relationship with AEE clearly improved the accuracy and the precision of the Actiheart combined ACC/HR AEE estimates. Similarly, Strath et al. (32), in a reanalysis of their 10-h field data using combined ACC and HR to estimate AEE, found a significant increase in precision when using individual calibration as compared with group-calibrated equations. In our study, this improvement was more important in lean active subjects, indicating that the group calibration equations are less appropriate in these subjects. With the use of the low-to-moderate intensity step-test of the Actiheart software, Assah et al. (1) also reported that the bias of their free-living combined ACC/HR AEE estimates was reduced significantly with individual calibration of HR, but the accuracy still remained unchanged in their study. Whether this was related to the specificity of their population or to the use of a more simple calibration procedure or still remained to be determined. On the other hand, the use in our study of a cycle ergometer exercise, imposed by our training protocol, may not have been the most adequate for the estimation of AEE related to everyday PA. A different cardiovascular response is generally reported for treadmill and cycle exercise, with HR higher on the cycle than on the treadmill for the same submaximal AEE (17). This raises the more general question of the representativeness of the HR relationship with AEE derived from activities of various types and intensities performed in the laboratory for a free-living situation.

We are unaware of previous studies that have directly compared intervention-induced ΔAEE estimated from an accelerometer against DLW in adults. Cross-sectional correlations between the second set of combined ACC/HR AEE estimates and the corresponding DLW-AEE measures were lower than the correlations observed with the first set of data for all of the models. This result was expected and is likely explained by the intervention that we imposed to the subjects, which reduced variability in AEE for the second set of data. Nevertheless, our results further indicate that the Actiheart can reasonably be used to evaluate changes over time at the group level as long as individual calibration is used. However, two calibrations are to be performed if one wants to evaluate ΔAEE that are associated with fitness changes.

A general shortcoming of HR monitoring over a long time period is the issue of data quality due to potential interferences from electrical appliances or poor skin contact with the electrodes used to clip the Actiheart unit on the chest. In our study, due to a high compliance of subjects who regularly changed the electrodes throughout the DLW period, the loss of data was negligible during the first part of the study. When it occurs, it

was overcome easily by the use of the recovery and interpolation algorithm of the Actiheart software. However, despite the use of hypoallergenic electrodes, several local skin problems were reported. These side-effects associated with the constraints of wearing the electrodes explained that five out of the 35 subjects refused to wear the Actiheart for the second period, and that data of three additional subjects were too noisy to be used. The recent availability of thoracic belts on which the Actiheart units are fixed should limit these problems and constraints. As reported previously with waist-worn RT3 (21), most subjects reported that these devices were acceptable to wear.

One limitation of our study is the small sample size that limits the power to make valid subgroup analyses, which is partly compensated for by the high accuracy and precision of the DLW method. In addition, the population was composed exclusively of men. However, the design gave us the opportunity to study volunteers with a wide range of BMI and activity levels, indicating that our results should be applicable to the occidental adult population. Since our protocol ensured that the subjects had stable weight throughout the intervention, we can exclude that ΔAEE were explained by changes in body mass. Also, it should be noted that the intervention was mainly based on an aerobic program composed of ergometer sessions, which are poorly captured by ACC, suggesting that different results may have been obtained with other types of interventions.

Several approaches have been considered to eliminate limitations of ACC-based estimations of AEE. AEE estimates obtained by combining accelerometers with body temperature and galvanic skin response have been shown to have a modest accuracy with a significant mean bias (0.9 kJ/day) and ~50% of the DLW-AEE explained (31). The recognition of different postures and physical activities, made possible by using detailed temporal-information, new-generation piezoresistive, and capacitive-inertial sensors or multiunit systems should significantly improve the estimation of AEE by disentangling the issue of the variable relationship between activity counts and energy expenditure for different activity types (8). Today, none of these systems has yet been validated in free-living conditions nor are they commercially available.

In conclusion, the results of the present study support a good level of agreement between the Actiheart ACC/HR combined models and DLW for measuring AEE in lean and overweight men with varying PA levels, with a clear improvement by individual calibration of the HR relationship with AEE. Although this study was obtained using a calibration based on an exercise-tolerance test, results obtained in laboratory tests and in a similar study in subjects studied in free-living conditions indicate that an easy-to-use step-test, as proposed by the built-in software, could possibly be used to obtained reasonable estimates of individual daily AEE in free-living conditions. Our results indicate further that this portable monitor can also be used, as long as some precautions are taken, and individual calibration is used to test the effects of prevention interventions or experimental trials on PA.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

Author contributions: S.B. and C.S. conception and design of research; A.B., E.A., S.B., and C.S. performed experiments; C.V., J.D., H.R., A.C.M., S.B., and C.S. analyzed data; D.A.S., S.B., and C.S. interpreted results of experiments; C.S. prepared figures; C.S. drafted manuscript; A.B., D.A.S., E.L., S.B., and C.S. edited and revised manuscript; C.V., A.B., J.D., E.A., D.A.S., H.R., A.C.M., E.L., S.B., and C.S. approved final version of manuscript.

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