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An evaluation of the IDEEA™ activity monitor for estimating energy expenditure

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Abstract

Objective estimates of activity patterns and energy expenditure (EE) are important for the measurement of energy balance. The Intelligent Device for Energy Expenditure and Activity (IDEEA) can estimate EE from the thirty-five postures and activities it can identify and record. The present study evaluated the IDEEA system's estimation of EE using whole-body indirect calorimetry over 24 h, and in free-living subjects using doubly-labelled water (DLW) over 14 d. EE was calculated from the IDEEA data using calibration values for RMR and EE while sitting and standing, both as estimated by the IDEEA system ($IDEEA_{est}$) and measured by indirect calorimetry ($IDEEA_{meas}$). Subjects were seven females and seven males, mean age 38·1 and 39·7 years, mean BMI 25·2 and 26·2 kg/m^2, respectively. The $IDEEA_{est}$ method produced a similar estimate of EE to the calorimeter (10·8 and 10·8 MJ, NS), while the $IDEEA_{meas}$ method underestimated EE (9·9 MJ, $P<0·001$). After removing data from static cycling, which the IDEEA was unable to identify as an activity, both the $IDEEA_{est}$ and $IDEEA_{meas}$ methods overestimated EE compared to the calorimeter (9·9 MJ, $P<0·001$; 9·1 MJ, $P<0·05$ and 8·6 MJ, respectively). Similarly, the IDEEA system overestimated EE compared to DLW over 14 d; 12·7 MJ/d ($P<0·01$), 11·5 MJ/d ($P<0·01$) and 9·5 MJ/d for the $IDEEA_{est}$, $IDEEA_{meas}$ and DLW, respectively. The IDEEA system overestimated EE both in the controlled laboratory and free-living environments. Using measured EE values for RMR, sitting and standing reduced, but did not eliminate, the error in estimated EE.

Key words: Physical activity: Accelerometry: Exercise: Energy expenditure

Lack of physical activity ranks alongside smoking and obesity in the WHO estimates of long-term health risk for high-income countries[1]. It is generally accepted that modern populations are less active than would be beneficial for health, and that the public at large should be encouraged to increase their physical activity. Exercise programmes and increased levels of physical activity have a small but beneficial effect on weight loss[2,3], but are more important for successful maintenance of weight loss[4–6], and in the prevention of weight gain[6–8]. While it is important to encourage people to increase physical activity, most people do not have good objective measures of either their physical activity patterns or of the energy they expend in activity, which makes it difficult for a person to know exactly to what degree they are changing their behaviour or energy balance. Furthermore, people tend to gauge their activity through perceived exertion (which is inversely proportional to fitness) rather than energy expenditure. Thus, someone who is unfit may feel that they have expended a lot more energy than someone who is fit, during the same time period of activity. Measuring energy expenditure and providing quantitative estimates of physical activity patterns in free-living individuals would greatly help them incorporate activity into their daily lives, accurately quantify their activity behaviours and know the likely effect this would have on their energy balance. A quantitative, objective measure would help in monitoring physical activity in fitness training or weight-loss programmes. At present, techniques to do this are limited and there is a constant search for

Abbreviations: DiOGenes, Diet, Obesity and Genes; DIT, diet-induced thermogenesis; DLW, doubly-labelled water; HR, heart rate; IDEEA, Intelligent Device for Energy Expenditure and Activity; $IDEEA_{est}$, energy expenditure from the IDEEA system using estimated energy expenditures for sitting and standing, and RMR; $IDEEA_{meas}$, energy expenditure from the IDEEA system using measured energy expenditures for sitting and standing, and RMR; PAEE, physical activity energy expenditure; TDEE, total daily energy expenditure.

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new user-friendly techniques that can unobtrusively measure moment-by-moment activity patterns and energy expenditure at the individual level, so that this can be summed over periods of 24 h.

Total daily energy expenditure (TDEE) can be measured relatively easily in free-living subjects using doubly-labelled water (DLW)[9] or heart-rate (HR) monitoring[10]. By measuring, or estimating, RMR, and assuming the contribution of diet-induced thermogenesis (DIT), the energy expenditure associated with volitional activity, or physical activity energy expenditure (PAEE) can be deduced. However, the DLW method only gives a mean daily value over a period of 10–14 d and provides no information on the types or intensities of activities performed. Accelerometers (triaxial or uniaxial) go some way towards this, but they do not have the capacity to differentiate between non-load-bearing and load-bearing activities (e.g. walking and walking carrying something), or the energy cost of some specific activities such as those involving upper body movements[11]. Accelerometry has been combined with HR monitoring, to improve estimates of activity patterns and energy expenditure[12–14].

The Intelligent Device for Energy Expenditure and Activity (IDEEA, MiniSun) is capable of identifying thirty-five activities and postures and, when incorporated with basic subject anthropometry, provides an estimate of energy expenditure. Currently, most of the published work on the IDEEA have been on laboratory-based validation studies of energy expenditure[15,16], and gait and posture analysis under carefully controlled conditions with close investigator supervision of the subjects[17–20], usually over short measurement periods of less than a day. The IDEEA system was used in a subsample of free-living subjects in the Diet, Obesity and Genes (DiOGenes) study[21] to measure patterns of physical activity, and estimate energy expenditure in free-living subjects and over periods of three consecutive days. The IDEEA activity monitors were modified by the manufacturer to increase the data collection time from the nominal 24 h of the standard model by replacing the full electrocardiogram recording function with HR in beats per min. Pilot testing showed that the modified IDEEA could record data for at least three full days; the limiting factor being battery life.

The aims of the present study were to evaluate the IDEEA in (1) estimating energy expenditure against the 'gold standard' methods of whole-body indirect calorimetry, and under free-living conditions using DLW, (2) comparing energy expenditure estimates when using measured rather than estimated calibration values and (3) identifying a limited range of postures and activities.

Research methods and procedures

Subjects

For the present study, eight female and seven male subjects were recruited from Aberdeen, UK through advertisements. All subjects were healthy, aged 20–55 years, non-smokers, not undertaking dietary or exercise treatments to lose weight, and had a recent history of weight stability. Subjects were informed orally and in writing about the procedures and written consent was obtained. On completion, subjects received a gratuity of £50.

Experimental design

Each subject was studied once in a 14 d protocol. Subjects were instructed to wear an IDEEA activity monitor throughout the protocol, except when bathing, swimming and optionally at night. For a detailed description of the IDEEA activity monitor, see Zhang *et al.*[18].

On days 1 and 14, subjects were resident in a whole-body indirect calorimeter for 24 h. The whole-body indirect calorimeters at the Rowett Research Institute are 14·5 m^3 in volume, contain a single bed, chair, table, television, exercise bicycle, wash basin and a small toilet cubicle. O_2 consumption and CO_2 production were estimated by using the rapid-response calculations of Brown *et al.*[22]. Energy expenditures were calculated from O_2 and CO_2 exchanges using the equations of Livesey & Elia[23].

The gas analysers were calibrated before every run using atmospheric gas, N_2 and a span scaling gas, and adjusted accordingly when barometric pressure had been accounted for. The span gases were checked by comparison with α standard gases, corrected to standard temperature and pressure (British Oxygen Company). During the run, the analysers were corrected for drift every 3 h with the use of atmosphere as a reference. Initial calibration of the flowmeters and gas analysers was performed by measured gas release using a wet flowmeter (Midget: Alexander Wright). The accuracy of the whole system was tested by performing six, 60 min butane burns once the chamber had been primed by prior burning of butane. This procedure enabled the agreement between the observed and expected values for O_2 consumption and CO_2 production to be qualified. All results were corrected to give 100 % recovery of both gases.

Between the two calorimetry periods, subjects were free to go about their daily lives apart from returning to the Human Nutrition Unit at the Rowett Research Institute every 2 or 3 d (see the following text). Before the study, subjects underwent a series of measurements. Height was measured to the nearest 0·5 cm, using a stadiometer (Holtain Limited). Subjects were weighed (corrected to nude) in the morning after voiding and before eating, to the nearest 50 g on a digital scale (DIGI DS-410; CMS Weighing Equipment Limited). O_2 consumption and CO_2 production were measured in fasting subjects during the morning using a ventilated hood system (Deltatrac II, MBM-200; Datex Instrumentarium Corporation). RMR was calculated for each subject from the volume of O_2 (VO_2) consumed and volume of CO_2 (VCO_2) produced each min, where $\text{RMR (MJ/24 h)} = ((15{\cdot}818 \times VO_2) + (5{\cdot}176 \times VCO_2)) \times 1{\cdot}44/10^{-3}$[24].

To establish the individual relationship between HR and energy expenditure for each subject, a sub-maximal calibration procedure was conducted on the same morning as, and immediately after, the RMR measurement. HR and breath-by-breath VO_2 and VCO_2 were measured (averaged over 10 s intervals) using a Vmax29 metabolic cart (Sensor

Medics) during sedentary routines and active routines of incremental workloads on a bicycle ergometer (Tunturi E850; Tunturi) in the following sequential steps with no break between them: 5 min sitting, 5 min standing up, 5 min cycling at the lowest possible resistance (55 W), and further 5 min blocks of increasing cycling resistance while maintaining a cadence of 60 rpm.

Cycling resistance was increased by 50 W, as indicated by the bicycle ergometer, for each block of the sub-maximal test. The test continued until the subject had cycled for at least three of these incremental stages, depending on the individual's level of fitness, and HR had reached approximately 150 beats per min. Average energy expenditures for each activity, and at each workload, were estimated from VO_2 and VCO_2 values using the equations as given earlier[24].

Intelligent Device for Energy Expenditure and Activity monitor

Subjects wore an IDEEA activity monitor from the start of day 1 until the end of the second calorimetry period on the morning of day 15, except when bathing or swimming. During the free-living period, they were permitted to remove the IDEEA at night if they wished. The IDEEA were worn continuously during the calorimetry periods, including during the night. Subjects were trained in the correct positioning of the IDEEA's eight sensors, and they were provided with written instructions and diagrams for refitting the sensors.

The IDEEA system can either use its own estimates of RMR and the energy expenditures of sitting and standing, or these values can be substituted with measured values. IDEEA data files were analysed using the manufacturer's software, initially using the default estimated RMR and energy expenditure values for sitting and standing ($IDEEA_{est}$), and then with measured values ($IDEEA_{meas}$) obtained during the RMR measurement and sedentary routines (sitting and standing only) of the sub-maximal calibration procedure. Using the IDEEA's software, activity codes and energy expenditure values were generated using a 1 min average for the calorimetry periods, and a 10 s average for the free-living period and when assessing the accuracy of the IDEEA in identifying postures and activities during the calorimetry protocol. TDEE were adjusted to include the energy cost of DIT, assumed to be 10 % of energy intake[25]. DIT is included in the measurement by the reference calorimetric methods, but is not accounted for by the IDEEA system. Then, 10 % of actual energy intake was added to the $IDEEA_{est}$ and $IDEEA_{meas}$ estimates of energy expenditure during the calorimetry period. For the free-living period, 10 % of mean daily reported energy intake was added to each day's energy expenditure estimate. Energy expenditure values during the 8 h lights-out period in the calorimeter were replaced with sleeping metabolic rate value, taken to be 95 % of BMR[26]. Periods where the subject did not appear to have worn the IDEEA (during the free-living period only) were considered to be missing data and were identified from blocks of data where both the activity codes and HR did not change for six or more consecutive 10 s average values (i.e. 1-min). The IDEEA's energy expenditure estimates during these periods were replaced with individual sleeping metabolic rate values for up to 8 h data per d for time spent asleep. Any subsequent energy expenditure estimates from periods of missing data, above 8 h, were calculated as the individual mean energy expenditure value taken from values when the IDEEA was worn and using the whole 12 d free-living data.

Estimation of energy expenditure from heart rate

Energy expenditure was also estimated from HR data collected by the IDEEA, using the Flex heart-rate (FLEXHR) method[27,28]. To equate HR to energy expenditure, a regression line of HR to energy expenditure was established for each subject from the sub-maximal calibration procedure, using measurements from when subjects were sitting, standing and at each of the workloads.

The critical HR, below which the relationship between HR and energy expenditure is non-linear, referred to as FLEXHR, was calculated from the mean of the highest HR when the subject was standing, and the lowest HR when exercising[29]. Average values from the HR data recorded by the IDEEA system were calculated for 1 min intervals for the calorimetery periods and 10 s intervals for the free-living periods.

Energy expenditure was estimated using the subject-specific regression equation where the average HR was $>$FLEXHR, and a mean sedentary expenditure level where HR was $\leq$FLEXHR. The mean sedentary expenditure was calculated from the mean energy expenditure during the RMR, sitting and standing measurements of the calibration procedure[27].

Energy expenditure during periods when there were no HR data (because the IDEEA did not appear to have been worn) was assumed to be sleeping metabolic rate up to a maximum of 8 h/d, and the mean sedentary expenditure level at other times[29].

Also, 10 % of energy intake was added to the estimate of energy expenditure during the calorimetry and free-living periods as described for the IDEEA method previously.

Free-living period

Subjects returned to the Human Nutrition Unit every 2 or 3 d to allow data from the IDEEA to be downloaded and the battery to be replaced, and to transfer urine samples for the DLW analysis. Urine samples were stored at −20°C until analysis.

Dietary data were collected for the fourteen consecutive days of the study period using the weighed-record method[30]. All weighing scales were calibrated with standard weights before use by the subjects. Food records were analysed using Diet5 for Windows (Univation Limited, The Robert Gordon University), which uses UK food composition data[31] to calculate energy intake and nutrient composition.

The energy cost of weight change over the diary recording period was estimated, assuming that 75 % of any weight gained was adipose tissue and 25 % was lean tissue, and using an energy value of 26·2 MJ/kg for weight loss and 33·7 MJ/kg for weight gain[32].

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Calorimeter periods

Subjects entered the calorimeter at 07.30 hours on day 1 and day 14 of the protocol, and the 24 h measurement period started at 09.00 hours. A medium-fat diet (40, 47 and 13 % energy from fat, carbohydrate and protein, respectively) was provided, which supplied 1·6 × RMR. Subjects exercised on a cycle ergometer (Monark) at 50 W, for two periods of 45 min each, to elevate their 24-h energy expenditure to about 1·6 × RMR. The IDEEA system is unable to detect cycling as an activity (whether on an exercise or real cycle), and usually allocates a stationary sitting or standing posture, or a sitting or standing with leg(s) moving activity with an estimated energy expenditure that is unrelated to the work being done. Consequently, the IDEEA underestimates energy expenditure during cycling. Energy expenditures during the calorimetry period were calculated both including the cycling periods (24 h values), and excluding data from the two 45 min cycling periods and approximately 5 min afterwards, until energy expenditure estimated from the calorimeter data returned to pre-exercise values (22 h values).

There were two periods of controlled activities, which were supervised by a researcher, starting at 15.15 hours and 21.15 hours, to assess the IDEEA's ability to identify activities and to estimate the energy expenditure of specific postures and activities. Subjects adopted the postures and underwent the activities described in Table 2 for 5 min each. Activity codes assigned by the IDEEA system were compared to the postures and activities of the subjects, and the number of correct, incorrect and similar (e.g. where the IDEEA system correctly identified that the subject was lying down, but incorrectly identified the orientation as 'lying on back' instead of 'lying on front'), matches totalled.

Outside the cycling, controlled activities, meal times and night, subjects were free to read or watch television.

Double-labelled water technique

The DLW technique was used to estimate energy expenditure over the complete study period from day 1 to day 14 inclusive, and comprised of 2 d when the subjects were in the calorimeter, and the 12 d in-between when they were free-living. Subjects were dosed with DLW on the morning of day 1. A pre-dose urine sample and a background sample, collected on day 1, were used to assess baseline (pre-dose) isotopic enrichments of the subject's body water pools. Subjects with an initial body weight ≤100 kg received a dose comprising of 10 g of a 99·9 % $^{2}H_2O$–H_2O mixture and 90 g of a 10·0 % $H_2^{18}O$–H_2O mixture. Subjects over 100 kg initial body weight received 10 and 110 g, respectively. Urine samples were then collected at 4 and 6 h after dosing to enable plateaus to be individually measured using the 'slope intercept' method[9]. Subjects were asked to collect a second void urine sample, approximately 30 min after the first morning void, each day for the following 14 d, and record the exact time of collection. Urine samples were collected for a multi-point stable-isotope analysis using gas isotope ratio mass-spectrometry. Isotopic enrichment of the post-dose urine samples was analysed relative to the original background amounts. Pool sizes and flux rates were calculated as described by Coward[33].

Measures of physical activity energy expenditure

PAEE was calculated from the DLW measurements as PAEE = TDEE – RMR – DIT. For the $IDEEA_{est}$, $IDEEA_{meas}$ and HR methods, PAEE = TDEE – RMR.

TDEE was also scaled for body size by dividing each TDEE by body weight.

This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving human subjects were approved by the Grampian Research Ethics Committee. Written informed consent was obtained from all subjects.

Statistical analyses

The accuracy of the IDEEA system in estimating energy expenditure was calculated as:

$$(\text{IDEEA system's estimate}/\text{the reference method}) \times 100.$$

Energy expenditure values estimated by the IDEEA, HR and reference methods (calorimeter or DLW) were compared using Student's *t* tests. Pearson correlation coefficient, Lin's concordance coefficient[34] and Bland–Altman plots[35] were used to test for agreement between methods.

Energy expenditure values from more than two methods were compared using ANOVA. Data were analysed using the SPSS version 11.5.0 statistical package. Statistical significance was accepted at the 5 % probability level.

Results

Data from one female subject were insufficiently complete and were unusable (both calorimeter measurements, and much of the IDEEA data were lost because of equipment failure). This subject was excluded from the analysis.

Energy expenditure by DLW was not calculable for two male subjects because of incomplete or poorly recorded urine collection times. One male subject lost his food intake diary; energy intake during the free-living was assumed to be equal to 1·6 × RMR when estimating DIT. Results presented here are from all seven female subjects and seven male subjects, except for the values relating to the energy expenditure estimation by the DLW technique, which are from five male subjects (and seven female subjects), and energy intake, which are from six male subjects (and seven female subjects).

The IDEEA monitors were worn by subjects for an average of 63 (SD 5·3) % of the free-living time. Most of the missing time was at night.

Subject characteristics are presented in Table 1.

Energy expenditure estimates under controlled conditions

There was no significant difference in total energy expenditure between $IDEEA_{est}$ and the calorimeter over the 24 h calorimetry period. Lin's concordance coefficient was 0·934 and the correlation between the two estimates was R^2 0·890 ($P<0·001$). The HR method produced an overestimate of energy expenditure, compared to the calorimeter, of 0·96 (SD 1·66) MJ over the calorimetry period ($P=0·049$); Lin's concordance coefficient was 0·774 and R^2 0·828 ($P<0·001$).

The IDEEA$_{meas}$ estimate of energy expenditure over the calorimetry period was, on average, 0·90 (SD 0·74) MJ lower than that of the calorimeter ($P<0·001$). Lin's concordance coefficient was 0·874, and the correlation R^2 0·911 ($P<0·001$). The accuracies of IDEEA$_{est}$ and IDEEA$_{meas}$ were 99·7 (SD 7·3) and 91·2 (SD 7·1) %, respectively. The difference between the measures of energy expenditure by the IDEEA and calorimeter was not associated with subject's height, weight, BMI, sex or age.

Both the IDEEA$_{est}$ and IDEEA$_{meas}$ methods underestimated the energy expenditure during the two periods of static cycling activity compared to the calorimeter. The mean values were 8·3 (SD 3·42) kJ/min for the IDEEA$_{est}$ method, 7·4 (SD 3·44) kJ/min for the IDEEA$_{meas}$ method and 22·8 (SD 4·61) kJ/min for the calorimeter (both differences $P<0·01$) (Table 1). After removing the energy expenditure values from the two periods of cycling, both the IDEEA$_{est}$ and IDEEA$_{meas}$ methods overestimated energy expenditure compared to the calorimeter by 1·25 (SD 0·73) MJ, $P<0·001$ and 0·46 (SD 0·64) MJ, $P<0·05$, respectively. The accuracies of the two estimates were 114·4 (SD 7·1) and 104·9 (SD 6·5) %.

The difference between the HR method and the calorimeter was borderline significant (0·78 (SD 1·41) MJ, $P=0·058$).

The body weight-adjusted IDEEA$_{est}$ values for the complete 24 h calorimetry period were not significantly different from the calorimeter values, whereas the IDEEA$_{meas}$ values were significantly lower (Table 1). The mean difference from the calorimeter, and the limits of agreements (mean difference ± 2 SD) were −0·74 (−22·7, 21·2) kJ/kg per d and −13·3 (−36·2, 9·6) kJ/kg per d for the IDEEA$_{est}$ and IDEEA$_{meas}$, respectively, with correlations of R^2 0·546 and R^2 0·459, and Lin's concordance coefficients of 0·738 and 0·453, respectively.

Removing the energy expenditure measures of the cycling activity resulted in the IDEEA$_{est}$ values being significantly higher than the calorimeter values, while the IDEEA$_{meas}$ was not significantly different. The mean difference from the calorimeter and the limits of agreement were for the IDEEA$_{est}$ and IDEEA$_{meas}$, respectively, 12·1 (−7·9, 32·0) kJ/kg per 22 h and −3·9 (−24·5, 16·8) kJ/kg per 22 h. The correlations to the calorimeter values were R^2 0·539 and R^2 0·399, with Lin's concordance coefficients of 0·484 and 0·594.

Identification and energy expenditure of postures and activities. On average, the IDEEA system identified the controlled postures and activities correctly 63 %, similarly 20 % and incorrectly 17 % of the time (Table 2). This varied greatly between subjects (Table 3).

Table 1. Subject characteristics for females, males and all subjects from the pre-study measurements and energy expenditures during the calorimetry measurement periods

(Mean values and standard deviations)

	Females		Males		All	
	Mean	SD	Mean	SD	Mean	SD
n	7		7		14	
Age (years)	38·1	12·0	39·7	9·4	38·9	10·4
Height (m)	1·63	0·05	1·78	0·09	1·71	0·10
Weight (kg)	67·2	12·8	83·4	23·4	75·3	20·0
BMI (kg/m^2)	25·2	5·08	26·2	6·39	25·7	5·57
Energy expenditure including cycling exercise (24 h)						
TDEE calorimeter (MJ)	9·5	1·1	12·1	2·1	10·8	2·1
TDEE IDEEA$_{est}$ (MJ)	9·2	1·02	12·4	2·5	10·8	2·4
TDEE IDEEA$_{meas}$ (MJ)	8·4	1·2	11·4	2·4	9·9***	2·4
TDEE heart rate (MJ)	9·9	2·3	13·6	3·3	11·8*	3·3
TDEE/kg calorimeter (kJ/kg)	146	19	147	12	147	15
TDEE/kg IDEEA$_{est}$ (kJ/kg)	142	16	150	15	146	15
TDEE/kg IDEEA$_{meas}$ (kJ/kg)	129*	13	138*	12	133*	13
TDEE/kg heart rate (kJ/kg)	150	20	165	27	158	24
PAL†	1·73	0·14	1·65	0·10	1·69	0·12
Energy expenditure excluding cycling exercise (22 h)						
Calorimeter (MJ)	7·5	1·0	9·7	1·7	8·6	1·7
IDEEA$_{est}$ (MJ)	8·4***	0·9	11·3*	2·2	9·9***	2·2
IDEEA$_{meas}$ (MJ)	7·7	1·1	10·4*	2·1	9·1*	2·1
Heart rate (MJ)	7·7	1·9	11·1	2·6	9·4	2·8
TDEE/kg calorimeter (kJ/kg)	114	13	118	10	116	11
TDEE/kg IDEEA$_{est}$ (kJ/kg)	123*	15	133*	14	128***	15
TDEE/kg IDEEA$_{meas}$ (kJ/kg)	107	13	117	11	112	13
TDEE/kg heart rate (kJ/kg)	99	20	128	30	113	29

TDEE, total daily energy expenditure; IDEEA, Intelligent Device for Energy Expenditure and Activity; IDEEA$_{est}$, energy expenditure from the IDEEA system using estimated energy expenditures for sitting and standing, and RMR; IDEEA$_{meas}$, energy expenditure from the IDEEA system using measured energy expenditures for sitting and standing, and RMR; PAL, physical activity level.

Mean values were significantly different from that of the calorimeter: * $P<0·05$; ** $P<0·01$; *** $P<0·001$.

† PAL = energy expenditure from doubly-labelled water/RMR.

Table 2. Identification, and estimated and measured energy expenditures (EE) of controlled activities
(Mean values and standard deviations)

	Percentage of data points			EE								
				Calorimetry (kJ/min)		$IDEEA_{est}$ (kJ/min)		$IDEEA_{meas}$ (kJ/min)		Heart-rate (kJ/min)		
	Correct	Similar	Incorrect	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P*
Lie on bed (face down)	49	15	36	6·4	1·8	6·3	1·6	5·5*	1·51	6·0**	3·6	<0·001
Lie on bed (on back)	29	70	1	6·6	1·4	6·4	2·0	5·5*	1·70	5·1*	1·8	<0·001
Lie on bed (on right shoulder)	48	21	31	6·0	1·5	6·0	1·5	5·2*	1·37	5·1*	2·0	<0·001
Lie on bed (on left shoulder)	52	18	30	6·0	1·5	6·0	1·4	5·3*	1·37	5·1*	2·0	<0·001
Sit upright on chair	92	3	5	6·9	2·0	7·1	1·9	6·1*	1·87	6·3**	3·7	<0·001
Sit left leg crossed over right leg	71	29	0	5·9	1·5	6·8*	1·6	5·8	1·64	5·2*	2·1	<0·001
Sit right leg crossed over left leg	79	21	0	5·8	1·5	6·8*	1·6	5·8	1·63	6·1	3·4	<0·001
Stand upright	79	15	6	6·1	1·7	8·0*	2·4	7·0*	2·46	8·3*	4·5	<0·001
Stand upright with left foot on box	89	7	4	6·4	1·6	8·4*	2·1	7·4*	2·20	7·8*	4·3	<0·001
Stand upright with right foot on box	87	9	4	8·3	3·4	8·6	2·2	7·6	2·39	10·3*	6·5	0·002
Step tests: one step per s	50	9	41	22·3	9·2	23·4	16·1	22·2	16·11	24·5	9·5	NS
Step tests: one step per 2 s	36	4	60	25·4	9·1	20·5*	11·6	19·4*	11·59	23·6**	9·2	<0·001
Walk at one step per s	30	62	8	17·8	6·0	16·0**	4·2	14·9*	4·30	16·8**	7·2	<0·001
Walk at 3–4 steps per s	86	6	8	17·9	5·8	20·8*	6·9	19·6*	7·09	20·2*	7·1	NS
Mean	63	20	17	10·6	8·1	10·7	8·4	9·7**	8·4	10·7	8·8	<0·001
Static cycling	–	–	–	22·8	4·61	8·3**	3·42	7·4**	3·44	25·0**	5·86	<0·001

$IDEEA_{est}$, energy expenditure from the IDEEA system using estimated energy expenditures for sitting and standing, and RMR; $IDEEA_{meas}$, energy expenditure from the IDEEA system using measured energy expenditures for sitting and standing, and RMR.
Mean values were significantly different from the calorimetry EE measurement: * $P<0·05$; ** $P<0·01$.

The patterns of overall daily energy expenditure estimates were similar when examined in more detail in moment-by-moment activities. For each of the controlled activities, and when compared to the energy expenditure measurement from the calorimeter, the $IDEEA_{est}$ tended to give similar or higher estimates, and both $IDEEA_{meas}$ and the HR method tended to give similar or lower estimates (Table 2).

Energy expenditure estimates under free-living conditions

Table 4 gives the mean daily energy expenditure values as estimated by the $IDEEA_{est}$, $IDEEA_{meas}$ and HR together with that of the reference method (DLW) during the free-living period. Figs 1 and 2 show the difference against the mean for mean daily energy expenditure estimates from DLW and $IDEEA_{est}$ (Fig. 1), and $IDEEA_{meas}$ (Fig. 2).

The average difference in estimate of daily energy expenditure, compared to the DLW values, for the $IDEEA_{est}$ was an overestimate of 2·61 (SD 1·10) MJ/d ($P<0·001$), with a correlation of R^2 0·781 (Fig. 3) and Lin's concordance coefficient of 0·478. Energy expenditure estimated by HR was 1·64 (SD 2·16) MJ/d ($P<0·05$) higher than the DLW estimate (R^2 0·491, Lin's concordance coefficient = 0·519). Replacing the $IDEEA_{est}$ values with $IDEEA_{meas}$ values reduced the discrepancy between the two measures to 1·35 (SD 1·01) MJ/d ($P<0·001$), with a correlation of R^2 0·768 (Fig. 3), Lin's concordance coefficient = 0·701. Accuracy was 128 (SD 11·7) % and 115 (SD 11·2) % for $IDEEA_{est}$ and $IDEEA_{meas}$, respectively. Linear regression suggested that the difference

Table 3. Controlled activities by subject
(Mean values and percentages)

Sex	Age (years)	Height(m)	Weight(kg)	BMI (kg/m²)	Correct (%)	Similar (%)	Incorrect (%)
F	28	1·65	64·7	23·8	77	10	13
F	24	1·61	58·3	22·5	74	10	16
F	31	1·74	69·3	22·9	10	36	55
F	54	1·65	61·6	22·6	53	26	21
F	33	1·57	49·6	20·1	79	15	6
F	52	1·60	86·5	33·8	61	14	25
F	45	1·61	80·5	31·0	79	14	7
M	37	1·66	65·8	23·9	69	15	16
M	26	1·88	73·6	20·8	61	20	19
M	43	1·72	76·7	25·9	36	51	14
M	46	1·83	74·2	22·2	72	15	13
M	54	1·68	70·9	25·1	55	23	23
M	31	1·83	134·2	40·1	62	27	11
M	41	1·86	88·5	25·6	38	27	35
Mean					58·9	21·5	19·6

F, female; M, male.

Table 4. Daily energy intake and expenditure, and change in body weight over 14 d
(Mean values and standard deviations)

	Females		Males		All	
	Mean	SD	Mean	SD	Mean	SD
RMR (MJ)	5·6	0·7	7·5	1·5	6·5	1·5
TDEE DLW (MJ)	8·5	1·1	11·0	1·9	9·5	1·9
TDEE $IDEEA_{est}$ (MJ)	10·8**	1·3	14·6*	2·5	12·7**	2·8
TDEE $IDEEA_{meas}$ (MJ)	9·9**	1·6	13·1	2·4	11·5**	2·6
TDEE HR (MJ)	9·1	1·7	14·5*	1·4	11·8*	3·2
TDEE/kg DLW (kJ/kg)	130	14	151	22	139	20
TDEE/kg $IDEEA_{est}$ (kJ/kg)	166***	16	179*	30	173***	24
TDEE/kg $IDEEA_{meas}$ (kJ/kg)	151**	14	161	24	156***	20
TDEE/kg HR (kJ/kg)	140	28	181*	35	160*	37
PAEE DLW (MJ)	1·8	0·9	3·1	1·6	2·3	1·3
PAEE $IDEEA_{est}$ (MJ)	3·3**	0·8	4·4*	1·7	3·9***	1·4
PAEE $IDEEA_{meas}$ (MJ)	3·1*	0·9	3·8	2·5	3·4**	1·9
PAEE HR (MJ)	2·8	1·5	6·4*	1·9	4·6**	2·5
PAL†	1·52	0·14	1·61	0·2	1·56	0·2
Energy intake (MJ)	8·9	0·7	10·1	2·1	9·4	1·6
Change in body weight (kg/14 d)	−0·31	0·71	−0·59	0·59	−0·46	0·64

TDEE, total daily energy expenditure; DLW, doubly-labelled water; IDEEA, Intelligent Device for Energy Expenditure and Activity; $IDEEA_{est}$, energy expenditure from the IDEEA system using estimated energy expenditures for sitting and standing, and RMR; $IDEEA_{meas}$, energy expenditure from the IDEEA system using measured energy expenditures for sitting and standing, and RMR; PAEE, physical activity energy expenditure; HR, heart rate; PAL, physical activity level.
Mean values were significantly different from the DLW energy expenditure measurement: * $P<0·05$; ** $P<0·01$; *** $P<0·001$).
† PAL = energy expenditure from DLW/RMR.

between the IDEEA and DLW measures of energy expenditure was associated with subject's age for both $IDEEA_{est}$ and $IDEEA_{meas}$ (R^2 −0·362, P=0·039 and R^2 −0·539, P=0·007, respectively), and for subject's height for $IDEEA_{est}$ (R^2 0·396, P=0·028). There were no significant associations with subject's sex, weight or BMI.

Energy expenditures from $IDEEA_{est}$ and $IDEEA_{meas}$ were both significantly greater ($P<0·001$) than energy intake, as was energy expenditure from HR ($P<0·05$). Energy expenditure from DLW was not significantly different from reported energy intake.

The body weight-adjusted mean daily energy expenditure values during the free-living period from the $IDEEA_{meas}$ estimates were closer to the DLW values that were the $IDEEA_{est}$ values, but both were significantly higher for females, and for males and females combined (Table 4). The mean difference from the DLW values, and the limits of agreement were 38·1 (8·4, 67·8) and 19·6 (−9·6, 48·7) kJ/kg per d for $IDEEA_{est}$ and $IDEEA_{meas}$, respectively. The respective correlations were R^2 0·594 and R^2 0·526, with Lin's concordance coefficients of 0·280 and 0·471.

Estimates of physical activity energy expenditure

Estimates of PAEE by the $IDEEA_{est}$ method were significantly higher than those by the DLW method (Table 4) by an average of 1·7 MJ/d with limits of agreement of −0·5 and 3·8 MJ/d. The correlation between the two methods was R^2 0·414 (P=0·024) and Lin's concordance coefficient of 0·083.

Corresponding values for the $IDEEA_{meas}$ method were 1·3 MJ/d with limits of agreement of −2·7 and 4·5 MJ/d. The correlation between the two methods was R^2 0·356 (P=0·041) and Lin's concordance coefficient of 0·063.

Discussion

The present study assessed the IDEEA system's accuracy in estimating energy expenditure under controlled laboratory and free-living conditions, and evaluated the effects of replacing the system's estimated energy expenditure values of RMR, sitting and standing with measured ones. Compared to reference methods (indirect calorimetry), the IDEEA significantly overestimated energy expenditure in both the calorimeter and the field. Using measured RMR, sitting and standing values improved the accuracy of the IDEEA in the present study, although the IDEEA still gave a significant overestimate of energy expenditure.

Estimation of energy expenditure

The uncalibrated IDEEA appeared to give very good daily energy expenditure estimates, over the 24 h measurement period when averaged over the group of subjects, and average energy expenditures for the controlled activities The average accuracy (99·7 (SD 7·3) %) is better than the 95·2 (SD 2·3) % reported by Zhang *et al.*[15], who used the IDEEA system's estimates of resting energy expenditure ($IDEEA_{est}$). The studies were similar in design and execution, the main difference being that the exercise protocol to raise energy expenditure in the study reported by Zhang *et al.* was three periods of walking on a treadmill, rather than cycling on a bicycle ergometer.

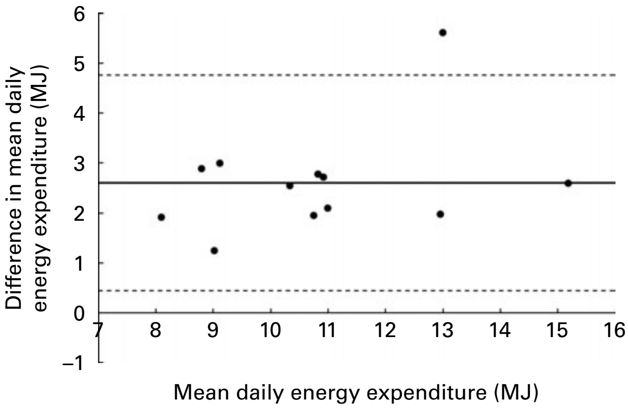

Fig. 1. Difference against mean for mean daily energy expenditure as estimated by doubly-labelled water and $IDEEA_{est}$. Horizontal lines are (——) mean (2·60 MJ/d), (- - -) 95 % CI (0·45 and 4·76 MJ/d). IDEEA, Intelligent Device for Energy Expenditure and Activity; $IDEEA_{est}$, energy expenditure from the IDEEA system using estimated energy expenditures for sitting and standing, and RMR.

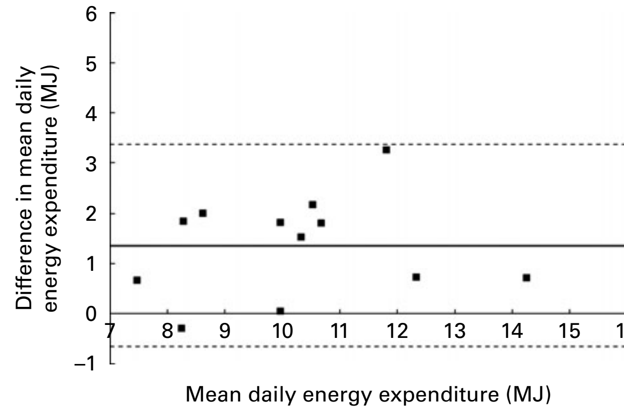

Fig. 2. Difference against mean for mean daily energy expenditure as estimated by doubly-labelled water and $IDEEA_{meas}$. Horizontal lines are (——) mean (1·35 MJ/d), (- - -) 95 % CI (−0·66 and 3·36 MJ/d). IDEEA, Intelligent Device for Energy Expenditure and Activity; $IDEEA_{meas}$, energy expenditure from the IDEEA system using measured energy expenditures for sitting and standing, and RMR.

The IDEEA system was unable to detect cycling as an activity. Removing data from the two cycling periods resulted in both the $IDEEA_{est}$ and $IDEEA_{meas}$ overestimating energy expenditure compared to the calorimeter, with average accuracies of 114 (SD 7·1) and 105 (SD 6·5) %. Thus, the overestimate of the energy expenditure by the IDEEA for most activities appeared to be cancelled out by the underestimate of energy expenditure during cycling. The energy expenditure during the exercise periods is unlikely to be the source of the difference in accuracy between the present study and that of Zhang *et al.* as this was removed from the analysis. Any excess post-exercise O_2 consumption that would have been recorded by the calorimeter, but not by the IDEEA, is likely to have been small because the cycling exercise was mild, and relatively short. Replacing the estimated calibration values with the measured ones in the present study reduced the discrepancy between the IDEEA and the calorimeter over the 22 h measurement period and lowered the energy expenditure estimate of each of the moment-by-moment activities. This had the effect of reducing the effect of the IDEEA's tendency to overestimate energy expenditure when using the system's calibration values, therefore reducing the total energy expenditure value over the calorimetry period.

The calibration activities used in the $IDEEA_{meas}$ method were the same as some of the controlled activities in the calorimeter, namely 'lie on bed (on back)', 'sit upright on chair' and 'stand upright'. The $IDEEA_{meas}$ produced significantly different estimates compared with the calorimeter for these activities where good agreement would be expected. Some of the difference between the values may be accounted for by the conditions under which the measurements were made. The RMR measurement was made in fasted and rested subjects, and was made over 30 min. The 'lie on bed (on back)' measurement in the calorimeter was made over 5 min, and was made 2 h after lunch and 3 h after dinner. The calorimeter measurement will include some DIT not present in the RMR measurement. The controlled activities measurement in the evening were made some 45 min after the subjects used the exercise bicycle, so that the subjects were not as rested as during the RMR measurement. The same differences also apply to the sitting and standing measurements.

The IDEEA did not correctly identify the standing activity all of the time (or, to a lesser extent, sitting), and this probably elevated the $IDEEA_{meas}$ and $IDEEA_{est}$ values.

Therefore, the true energy expenditures during the calorimeter measurements were probably slightly higher than during the same activities (lying, sitting and standing) used to calibrate the IDEEA for the $IDEEA_{meas}$ method.

Both the $IDEEA_{est}$ and $IDEEA_{meas}$ overestimated energy expenditure during the calorimeter period, when values from the two cycling periods were removed, with the $IDEEA_{meas}$ values being closer to the reference method. A similar pattern was seen during the free-living part of the study, with both methods overestimating energy expenditure, but the use of calibration values making an improvement. This was also seen when comparing the PAEE components of energy expenditure alone. The IDEEA system appears to overestimate the energy expenditure of movement, at least outside the laboratory. This overestimate is not always apparent under controlled conditions[15] where a limited range of activities has necessarily been evaluated, suggesting that the system is better able to detect, and estimate the energy expenditure of, some activities than others. In the calorimeter, the IDEEA underestimated the energy expenditure of slow walking, but overestimated faster walking. Other researchers have found better agreement using a more natural walking motion[20,36], including a treadmill[15], than was possible in the calorimeter in the present study. During the walking activities, subjects repeatedly took two or three steps and then turned around, and this may have been difficult for the IDEEA system to correctly identify as a walking activity, at least for a slow walk (Table 2). The difference in accuracy of energy expenditure estimation of the IDEEA system

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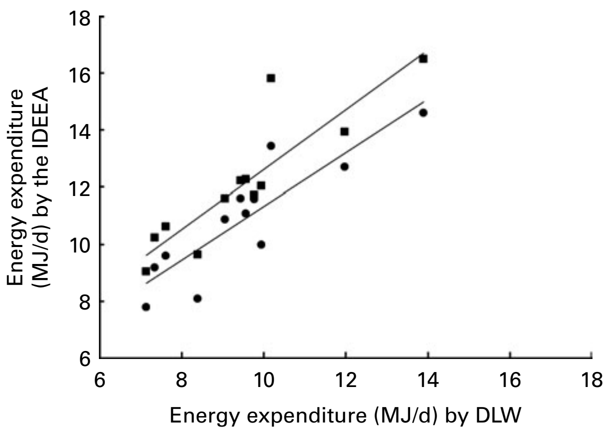

Fig. 3. Mean daily energy expenditure as estimated by doubly-labelled water (DLW), and $IDEEA_{est}$. (■, R^2 0·781) and $IDEEA_{meas}$ (●, R^2 0·768) techniques. IDEEA, Intelligent Device for Energy Expenditure and Activity; $IDEEA_{est}$, energy expenditure from the IDEEA system using estimated energy expenditures for sitting and standing, and RMR; $IDEEA_{meas}$, energy expenditure from the IDEEA system using measured energy expenditures for sitting and standing, and RMR.

between the present and previous studies[20,36,15] is probably due to the restrictions that the confined calorimeter placed on a natural walking motion, present in the current, but not the other studies.

In the present study, two subjects commuted to work by bicycle (approximately 90 min/weekday). PAL was highest for these two, but despite the IDEEA being unable to identify cycling, the accuracy of the IDEEA, compared to DLW, was among the highest for these two subjects.

The IDEEA system is primarily a device for short-term use, because of the relative difficulty of attaching the sensors, inconvenience and discomfort of wearing the sensors, and the memory capacity of the standard devices. On average, subjects wore the IDEEA for 63 % of the time, equal to just over 15 h/d, during the free-living part of the study (and 100 % during the calorimetry periods). Allowing 8 h/d for sleep and other daily activities when the IDEEA were not worn leaves about an hour each day when data were not recorded. Some of this may have been activities with high energy expenditures, such as swimming (the IDEEA are not waterproof). Thus, the estimates of activities and energy expenditure made using the IDEEA may be slightly low.

It was clear that using measured RMR, sitting and standing values improved the accuracy of the IDEEA when estimating energy expenditure in the present study. There appear to be no other studies that have reported the effects of using measured rather than estimated values.

Overall, the IDEEA appeared to be of similar accuracy in estimating energy expenditure to the HR method. The HR method is not without its difficulties also; it requires a more complex calibration procedure than for the IDEEA and provides no information on the type of activity, but is less intrusive for the subject and can be performed with inexpensive HR monitors.

Identification of postures and activities

The IDEEA correctly identified 63 % of the controlled activities in the calorimeter, with a further 20 % being identified as being similar to the true activities. The IDEEA was less accurate at identifying activities that involved motion than the static postures; as noted previously, this may be an effect of the limited space in the calorimeter restricting natural movement. Of the lying, sitting and standing postures, approximately 89 % were identified correctly or similarly, surprisingly low given the conditions of the measurements. The difference in energy expenditure between many correctly and similarly identified activities is likely to be small, such as 'lie on back' (correct) and 'lie down–facing down' (similar), and may not be important when estimating TDEE, or apportioning time spend being sedentary or active. It may be more problematic when looking at the energy expenditure of different activities in more detail, and differences in identifying walking movement may be critical in, for example, gait analysis. Furthermore, the determination of similar activities is subject to a degree of subjectivity.

Practicality of using the Intelligent Device for Energy Expenditure and Activity system. Of the intended 196 d IDEEA measurement in the present study (14 d for each of the fourteen subjects), 112 d (57·1 %) had ≥15 h data. Most of the missing data being from the night time, when energy expenditure can be predicted with acceptable accuracy. Taken together, these suggest that the IDEEA system would provide estimates of energy expenditure based on a complete day's activity for more than half of the measurement days. The IDEEA system was also used in free-living, overweight and obese subjects in the DiOGenes dietary intervention study[21]. A sub-group of 140 subjects agreed to wear the IDEEA for three consecutive days during each of three measurement periods. Some subjects dropped out of the study, or declined to wear the IDEEA more than once, resulting in 819 d on which the IDEEA should have provided activity data. Of these, there were 178 d (21·7 %) with ≥15 h data when the IDEEA appeared to have been worn, using the same criteria as in the present study. This increased to 43·5 % for ≥12 h. These subjects probably had different reasons for participating in the DiOGenes study, i.e. losing weight, than did subjects in the present validation study, and were probably less motivated to wear the IDEEA. The limited success in recording a large percentage of each day's activity highlights the difficulties of using the IDEEA system outside the controlled laboratory setting.

Limitations and potential of the Intelligent Device for Energy Expenditure and Activity to measure specific activities and daily energy expenditure

The IDEEA is one of the few devices capable of identifying the type and duration of activity that can be used outside the laboratory, albeit with an accuracy that may or may not be acceptable depending on the resolution required. In its present configuration, the IDEEA could be considerably improved, especially by moving to a wireless system with

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smaller sensors, greater data storage capacity and battery life. It is likely that both the hardware and the software capabilities now exist to take this interesting technique further.

Further development would also need to address the identification of additional activities such as cycling, which is a major contributor to total energy expenditure for some people. Arm movement is not currently detectable by the IDEEA, and the system is therefore unable to differentiate between stationary and some upper-body activities. Additional limb sensors, on the arms, may allow this but at a cost of further reducing usability.

A major limiting factor that still remains for the IDEEA or any derived device is that its accuracy seems to be influenced by the need to measure rather than estimate RMR, sitting and standing energy expenditure, at the individual level. This applies to the measurement of energy expenditure rather than the activities themselves, but it is important for moment-by-moment or TDEE. Measuring these calibration energy expenditures requires additional equipment that may not be readily available in some research centres, and adds complexity and time to the procedure of setting up the IDEEA, for a small gain in accuracy. New, less expensive and more portable devices to measure RMR by respiratory exchange are becoming increasingly available (e.g. St-Onge *et al.*[37]) and may be of value in developing a tool that allows individuals to record their specific activity and movement patterns, and the energy expenditure that is associated with them.

Given the current high cost of isotopic techniques to measure energy expenditure and the fact that they only provide a mean daily value of 10–14 d, there is considerable scope to develop a tool that can measure individual daily energy expenditure and the number and duration of activities that contribute to it. This would be of considerable value both to researchers and to people who want to change their activity behaviour and monitor both those changes and the impact they have on their overall energy balance.

Limitations

The present study, and hence some of the conclusions arising from it, is subject to a number of limitations. The generalisability of the results is limited by the small sample size. In particular, the subjects were mainly lean, or slightly overweight, and the range of body weights is probably too narrow to conclude that weight does not influence the accuracy of the IDEEA, for which there is some suggestion[38]. There was some evidence that subject's age and height were related to the IDEEA's accuracy, but again the ranges of these variables in this sample were limited.

Certain assumptions were necessary when estimating energy expenditure when the IDEEA were not worn during the free-living period. We assumed individual average energy expenditures for missing data during the day, which would have been too low for activities such as swimming that the IDEEA cannot record, and too high for sedentary activities such as sitting.

Processing of the raw data from the IDEEA's sensors is dependent on the manufacturer's software, the algorithms of which are not accessible to the researcher. It is not possible to evaluate exactly how the IDEEA system identifies activities or estimates energy expenditure. It is also not possible to assess what the contribution of the accelerometer sensors is towards the estimate of energy expenditure. Neither can the researcher determine exactly how the subject characteristics that are required by the IDEEA system (sex, age, weight and height) influence how the IDEEA system identifies the individual activities and postures, or how these subject characteristics contribute to the estimate of energy expenditure. The system is dependent on the IDEEA's software for post-data-collection processing, making it impossible for others to replicate the analysis without the appropriate version of the software. Therefore, the 'black-box' nature of the IDEEA system has imposed some limitations on this validation study, in that it was not possible to examine the source of all of the differences in energy expenditure estimate between the IDEEA and the reference methods.

Energy expenditure measurements by DLW were lost for two subjects, and this reduced the ability to make comparisons during the free-living period.

In conclusion, the IDEEA system produced a significant overestimate of energy expenditure, both when subjects were resident in the calorimeter and free-living. Using measured energy expenditure values for RMR, sitting and standing reduced the size of the overestimate, but the differences remained statistically significant.

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