



HAL
open science

Accuracy and validity of a combined heart rate and motion sensor for the measurement of free-living physical activity energy expenditure in adults in Cameroon.

Felix Kembe Assah, Ulf Ekelund, Soren Brage, Antony Wright, Jean Claude Mbanya, Nick Wareham

► To cite this version:

Felix Kembe Assah, Ulf Ekelund, Soren Brage, Antony Wright, Jean Claude Mbanya, et al.. Accuracy and validity of a combined heart rate and motion sensor for the measurement of free-living physical activity energy expenditure in adults in Cameroon.. International Journal of Epidemiology, 2010, 10.1093/ije/DYQ098 . hal-00598259

HAL Id: hal-00598259

<https://hal.science/hal-00598259>

Submitted on 6 Jun 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Accuracy and validity of a combined heart rate and motion sensor for the measurement of free-living physical activity energy expenditure in adults in Cameroon.

Journal:	<i>International Journal of Epidemiology</i>
Manuscript ID:	IJE-2009-12-1073.R1
Manuscript Type:	Original Article
Date Submitted by the Author:	21-Apr-2010
Complete List of Authors:	Assah, Felix; MRC Epidemiology Unit Ekelund, Ulf; MRC, Institute of Metabolic Science Brage, Soren; MRC, Institute of Metabolic Science Wright, Antony; MRC Human Nutrition Research Mbanya, Jean Claude; University of Yaounde I, Faculty of Medicine and Biomedical Sciences Wareham, Nick; MRC, Institute of Metabolic Science
Key Words:	physical activity energy expenditure , doubly-labelled water , heart rate monitoring, accelerometry, sub-Saharan Africa , validity

1
2
3
4
5
6
7
8 **Accuracy and validity of a combined heart rate and motion sensor for the measurement of**
9 **free-living physical activity energy expenditure in adults in Cameroon.**
10
11
12
13
14

15 Felix K. Assah¹, Ulf Ekelund¹, Soren Brage¹, Antony Wright², Jean Claude Mbanya³ and Nicholas J.
16
17 Wareham¹.
18
19
20
21

22 **Affiliations**
23

24 ¹Medical Research Council Epidemiology Unit, Institute of Metabolic Science, Addenbrooke's
25 Hospital, Cambridge, United Kingdom; ²Medical Research Council Human Nutrition Research,
26 Cambridge, United Kingdom; ³Faculty of Medicine and Biomedical Sciences, University of
27
28 Yaoundé 1, Yaoundé, Cameroon.
29
30
31
32
33
34
35

36 **Corresponding author:** Dr Ulf Ekelund, MRC Epidemiology Unit, Institute of Metabolic Science,
37
38 Box 285 Addenbrooke's Hospital, Hills Road, Cambridge, CB2 0QQ, UK . Tel: +44 (0) 1223
39
40 769208, Fax: +44 (0) 1223 330316, E-mail: ulf.ekelund@mrc-epid.cam.ac.uk.
41
42
43
44
45

46 **Word count:**
47

48 Abstract = 244
49

50 Text = 2992
51
52
53
54

55 **Keywords:**
56

57 Physical activity, energy expenditure, doubly-labelled water, heart rate monitoring, accelerometry,
58
59 sub-Saharan Africa, validity, accuracy.
60

Abstract

Background: The increasing burden of non-communicable diseases in sub-Saharan Africa warrants rigorous studies of contributing lifestyle factors. Combined heart rate and movement monitoring make it possible to objectively measure physical activity in free-living individuals. We examined the validity of a combined heart rate and motion sensor in estimating physical activity energy expenditure (PAEE) in free-living adults in rural and urban Cameroon compared to doubly-labelled water (DLW) as criterion.

Methods: PAEE was measured in 33 free-living rural and urban dwellers by DLW over 7 consecutive days. Simultaneously, the combined sensor recorded heart rate and uni-axial acceleration. Individual heart rate vs. PAEE calibration was done by a step test. Branched equation modelling was used to estimate PAEE from heart rate and acceleration. Validity and accuracy of prediction were expressed as mean bias and root mean square error (RMSE). Agreement was analyzed using Bland and Altman limits of agreement (LOA).

Results: There was no significant mean bias between PAEE estimated from the combined sensor or measured by DLW [mean bias (standard error): -5.4 (5.1) kJ/kg/day; $p=0.3$; RMSE=29.3 kJ/kg/day]. The bias doubled for group compared to individual calibration of heart rate (-9.1 (5.0) kJ/kg/day, $p=0.08$). PAEE prediction was more accurate in urban compared to rural volunteers. The 95% LOA between predicted and measured PAEE were about 50 to 60 kJ/kg/day above or below perfect agreement.

Conclusions: Combined heart rate and movement sensing is a valid method for estimating free-living PAEE on group level in adults in sub-Saharan Africa.

Introduction

Physical activity is beneficial for maintaining a healthy life and reducing premature morbidity and mortality.¹⁻⁸ However, a full understanding of the dose-response relationships between physical activity and health outcomes is still elusive. Objective and accurate measurement of physical activity is essential in elaborating these relationships.⁹ Nevertheless, the accurate measurement of physical activity in epidemiological studies still poses major challenges in terms of both feasibility and validity of the methods proposed.

Physical activity is a complex attribute that can be characterized in terms of volume, domains, type, duration, frequency and intensity. Many objective and subjective methods of measuring physical activity are available.¹⁰ However, the different dimensions of physical activity are not always adequately measured by a single method, producing conflicting results between objective and subjective measures in situations where both have been used to assess population-levels of physical activity.¹¹⁻¹³ Self-report methods may accurately rank individuals and can capture the specific domains of physical activity. However, their validity for estimating physical activity energy expenditure (PAEE) and time spent in different intensity levels of activity is usually poor.^{14;15}

Objective methods of measuring physical activity offer better prospects for accurately quantifying the total volume of physical activity or PAEE, and for most methods, its sub-components. Doubly-labelled water (DLW) is accepted as the gold standard method of measuring total energy expenditure (TEE) in free-living individuals, but its substantial cost has restricted its use to small validation or exploratory studies, almost exclusively carried out in Western industrialized countries.^{16;17} Accelerometers and heart rate (HR) monitors have been proposed separately¹⁸⁻²¹ and in combination^{22;23} as more feasible and pragmatic alternatives in measuring PAEE in free-living individuals. This combined sensing method has been validated in both in laboratories as well as in

1
2
3 free-living individuals. Laboratory studies use structured controlled activities, but may not really
4 represent free-living patterns of activity, particularly in a different population.
5
6

7
8 Validation and implementation of accurate and pragmatic objective methods of measuring
9 free-living physical activity in developing countries such as in sub-Saharan Africa (SSA) would
10 provide opportunity to clearly understand the determinants and effects of physical activity on the
11 current epidemiologic transition in this region.^{24;25} We have previously developed and validated
12 accelerometer-based regression equations which could be used to estimate free-living PAEE in
13 SSA.²⁶ However, accelerometry does not fully capture the inter-individual differences in PAEE
14 especially at high intensities.^{19;27} The incorporation of HR data with individual calibration of the HR
15 response to physical activity would remove inter-individual variability in true PAEE due to
16 differences in physiological parameters such as aerobic fitness.²⁸
17
18
19
20
21
22
23
24
25
26
27
28

29 The objective of this study was to examine the validity of a combined HR and motion sensor
30 in estimating PAEE in free-living individuals in Cameroon compared to DLW as criterion.
31
32
33
34
35

36 **Methods**

37 **Participants**

38
39
40
41
42
43 The participants were 35 adult volunteers recruited from an urban and a rural area of Cameroon, to
44 account for potential differences in physical activity due to urbanization.²⁹ Data on age and
45 occupational history were collected by self-report.
46
47
48
49

50
51 Ethical approval was obtained from the Cameroon National Ethics Committee and all
52 participants provided signed informed consent. One volunteer who withdrew from the study and
53 another who had a very rapid turnover of the DLW isotopes resulting in unrealistic data were
54 excluded from these analyses.
55
56
57
58
59
60

Resting energy expenditure

Resting energy expenditure (REE) was measured using the MedGem® handheld indirect calorimeter (HealthTech Inc., Golden, Colorado), previously validated in adults in field settings.^{30,31} The device measures oxygen consumption through breath-by-breath sampling over a duration of approximately 10 minutes. REE was calculated using the Weir equation³² assuming a respiratory quotient of 0.85. All measurements were performed under thermo-neutral conditions while the volunteers were sitting in a quiet room after an over-night fast and having refrained from caffeine, nicotine or exercise for at least 4 hours. REE was measured using breath-by-breath data collected for each volunteer over 8 to 10 minutes.

Free-living energy expenditure by DLW method

The DLW method was used as criterion measure of TEE for seven continuous days. Details of the procedure in this study have been previously reported.²⁶ Each volunteer drank a weight appropriate dose of DLW. Urine samples were collected approximately 24 hours before and after the administration of the DLW dose, and then daily for the next six days. The samples were analysed at the Medical Research Council Collaborative Centre for Human Nutrition Research, Cambridge, UK.

Isotopic enrichment of all samples was analyzed using procedures described in detail elsewhere.³³ Briefly, for $^2\text{H}/^1\text{H}$ ratios 0.4 ml sample was equilibrated with 3 ml H_2 gas at 1 bar and 22 °C for 6 hours in the presence of a Pt catalyst. The equilibrated gas samples were then measured relative to an arbitrary hydrogen reference gas using dual inlet isotope ratio mass spectrometry (Sira 10, Micromass, Wythenshaw, UK) and then enrichment values calculated on the SMOW/SLAP scale using laboratory references traceable to international standards. For ^{18}O , 0.5 ml samples were equilibrated with 10 ml 5% CO_2 in N_2 at 1 bar at room temperature, overnight. Ratio measurements were made using an AP2003 continuous flow isotope ratio mass spectrometer (Analytical Precision

1
2
3 Ltd, Northwich, Cheshire, UK) and enrichment values calculated on the SMOW/SLAP scale as
4
5 described for the ^2H data.
6
7

8 Rate constants for isotope disappearance were estimated using data from all the samples
9
10 collected over the 7-day period, after base-line correction using the pre-dose samples. If the rate of
11
12 ^{18}O disappearance exceeded 3 half-lives in this time, only samples taken up to 3 half lives were used
13
14 in the calculation of TEE to maintain an equivalence in precision.³⁴ Isotope dilution spaces were
15
16 calculated from the zero-time intercepts of the isotope disappearance curves.
17
18

19
20 TEE was calculated by means of standard equations;^{35;36} using Schoeller's estimation of CO_2
21
22 production, which normalizes $^2\text{H}/^{18}\text{O}$ space ratios to $1.04 / 1.01 = 1.03$. TEE was then calculated
23
24 from CO_2 production assuming a respiratory quotient of 0.85.³⁷ Average daily PAEE (kJ/day/kg)
25
26 was calculated as average 24-hr TEE minus awake resting (REE) and sleeping energy expenditure
27
28 ($=0.9 \times \text{REE}$) assuming an average daily sleep duration of 8 hours, minus 10% of TEE to account for
29
30 the thermic effect of food.
31
32
33
34
35

36 **Free-living PAEE by combined heart rate and movement monitoring**

37
38 Free-living PAEE was measured using a combined HR and movement sensor (Actiheart, Cambridge
39
40 Neurotechnology Ltd, Cambridge, UK). Initially, participants underwent an 8-minute step test^{38;39} at
41
42 a step height of 20 cm to provide individual calibration of HR to physical activity intensity.
43
44

45
46 Subsequently, free-living HR and acceleration were measured in one minute epochs using the
47
48 combined sensor over 7 continuous days, concurrently with the DLW measurement. The participants
49
50 were requested to carry on with their habitual lifestyle, carry the monitor at all times including when
51
52 awake or asleep. The monitors were to be taken off only for showering, bathing or activities like
53
54 swimming.
55
56
57
58
59

60 **Actiheart data processing and calculations**

1
2
3 Data from the Actiheart monitors were downloaded into a database using the Actiheart commercial
4 software. The same software was used to clean and recover or interpolate noisy and missing HR data
5 using the manufacturer's algorithm (www.camntech.com). HR data were converted to energy
6 expenditure using the individual calibration derived from the step test (HR_{STEP}) while the
7 accelerometer data was converted to energy expenditure using non-exercise calibrated accelerometry
8 equations corresponding to level walking or running (ACC).³⁹ A group calibration HR equation
9 (HR_{GROUP}) modified from the equation published by Brage et al³⁹ was used to assess the additional
10 benefit of using individual calibration compared to group calibration. The coefficients of the
11 regression parameters were modified using estimates from valid step tests in a different population-
12 based sample (N = 546) of the same target population. Physical activity intensity (PAI, J/kg/min)
13 equation for HR_{GROUP} :

$$PAI_{HR-GROUP} = 5.9 \cdot HR \text{ above sleep} + 0.5 \cdot HR \text{ above sleep} \times \text{gender} + 5.8 \times \text{gender} - 68.7$$

14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32 Minute-by-minute HR and movement derived PAI were combined in a branched equation
33 model⁴⁰ to calculate daily free-living PAEE. Separate acceleration and flex HR models (ACC or
34 HR_{FLEX}) were also used to estimate PAEE. Flex HR was estimated using a published sleeping HR-
35 based regression equation.³⁸ For all minutes above flex HR PAEE was estimated using the
36 individual HR to PAEE slope derived during the step test calibration. Below flex HR energy
37 expenditure was assumed to equal REE. Basal metabolic rate (\approx REE) was estimated from Schofield
38 equations⁴¹ and TEE was calculated by adding REE and a component for the thermic effect of food
39 (10% of TEE) to the derived PAEE. The distribution of intensity of activity was expressed as
40 average daily time spent below 1.5 METs corresponding to time spent asleep or sedentary, between
41 1.5 and 3 METs as time spent in light intensity physical activity (LPA), above 3 METs as time spent
42 in MVPA. Individual separate daily estimates were then collapsed to obtain individual mean
43 estimates using a probability weighting inversely proportional to the daily fraction of lost and
44 recovered data.
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Statistical analyses

Analyses were carried out using STATA® version 10.1 (StataCorp, College Station, Texas).

Descriptive characteristics of the study sample are presented as means with standard deviations and stratified by rural/urban residential area. Student's t-test was used to assess differences in the descriptive variables between the rural and urban volunteers. Unadjusted Pearson correlations were used to examine the association between PAEE derived from separate or combined HR and movement models, mean acceleration, mean HR above sleeping HR (HRaS) and time spent at different activity intensity levels with mean daily PAEE measured by DLW.

Criterion validity of the combined monitoring protocol against DLW measured PAEE was analyzed using Bland and Altman agreement method.⁴² The mean bias and the root mean square error (RMSE) between PAEE measured by DLW and estimated by the combined sensor were calculated. Sensitivity analyses were carried out to test the effect of outliers on the observed agreement.

Results

Table 1 presents some descriptive characteristics of the study sample. Rural-urban stratification was according to our a priori objective. The frequency of physically demanding jobs was higher among the rural compared to urban volunteers (76 and 25% respectively). Conversely, 61% of urban volunteers were engaged in mainly sedentary occupations. PAEE was about 31% higher in rural volunteers compared to their urban counterparts. A similar difference was observed when physical activity was expressed as PAL (=TEE/REE).

Table 2 presents correlations between PAEE derived from DLW with variables from combined HR and motion monitoring. There was a comparable positive correlation between PAEE

1
2
3 measured by DLW and estimated from the combined sensor with either individual or group
4
5 calibration. This correlation was stronger in urban compared to rural volunteers, and was accounted
6
7 for mainly by the correlation with movement variability (mean acceleration) than HR variability
8
9 (mean HRaS). PAEE predicted from the branched equation model (ACC+HR_{STEP}) accounted for
10
11 16% of the total variance in DLW-measured PAEE. Meanwhile, the separate HR_{FLEX} and ACC
12
13 models accounted for 10 and 29% of the total variance respectively.
14
15

16
17
18 There was no mean bias between mean PAEE estimated from combined HR and motion
19
20 monitoring or measured by DLW (Table 3 and Figure1). Furthermore, the mean bias between DLW-
21
22 measured PAEE and that estimated from combined HR and motion monitoring was almost halved
23
24 following individual step test calibration compared to group calibration, even though the RMSE was
25
26 largely unchanged. The accuracy of predicting PAEE from combined HR and motion monitoring
27
28 was always greater in the urban volunteers compared to their rural counterparts, with the RMSE
29
30 being almost 2 times greater in rural compared to urban volunteers. The LOA between predicted and
31
32 measured PAEE were wide, being about 50 to 60 kJ/kg/day above or below the measured value.
33
34 Similar to the RMSE, the LOA were 2 times wider in the rural compared to the urban volunteers.
35
36 Compared to the combined models, the separate ACC or HR_{FLEX} models were less accurate in
37
38 predicting DLW-measured PAEE (RMSE of 37.5 and 35.2 kJ/kg/day respectively). Moreover, the
39
40 ACC model underestimated DLW-measured PAEE ($p < 0.001$). These results did not change when
41
42 we re-analyzed the data omitting the 2 subjects who had large residuals (Figure 1). We also assessed
43
44 the influence of outliers by calculating Cook's D⁴³ and leaving out 3 subjects whose values were
45
46 greater than the conventional cut-off point of $4/n$ or 0.12. The results remained largely unchanged,
47
48 though the RMSE and the range of the LOA were reduced by about 30% (data not shown).
49
50
51
52
53
54
55
56
57

58 Discussion

59
60

1
2
3 In this study we have shown that PAEE derived from free-living HR (with individual or group
4 calibration) and movement monitoring using a branched equation modelling approach⁴⁰ was
5
6 positively correlated with DLW-measured PAEE. There was no mean bias between PAEE estimated
7
8 by the combined sensor compared to DLW in both rural and urban dwellers. The accuracy of
9
10 predicting PAEE from the combined sensor in urban dwellers was slightly better than in their rural
11
12 counterparts. However, these minor rural-urban differences did not affect the overall significance or
13
14 interpretation of our results. These results suggest that the combined HR and movement sensor could
15
16 be used in both rural and urban populations in SSA for measuring free-living activity in adults.
17
18
19

20
21 We have previously developed and evaluated PAEE prediction equations using
22
23 accelerometer (Actigraph) counts in this population.²⁶ Similar to our previous study,²⁶ movement
24
25 sensing captured the inter-individual variance in PAEE more strongly in urban than rural dwellers.
26
27 This may reflect differences in types and patterns of activities between rural and urban regions in
28
29 SSA. A higher prevalence of labour-intensive occupational activity (subsistence agriculture) in the
30
31 rural population would explain the negative rural-urban gradient in physical activity reported in
32
33 studies using self-report of activity,^{29;44} and which is evident even in this small validation study
34
35 using DLW. However, activities performed in rural areas involve much digging, lifting and load
36
37 carrying, which may not be fully captured by uni-axial accelerometers.⁴⁵⁻⁴⁷ Television viewing,
38
39 reading, needle work and leisure walking are among the most frequently reported leisure activities in
40
41 urban dwellers as opposed to light farming, animal rearing and leisure walking in rural dwellers in
42
43 Cameroon.²⁹
44
45
46
47
48
49

50 Previous studies have validated free-living HR monitoring using the Flex HR methods
51
52 against DLW for estimating PAEE.^{18;48} Combining HR data with accelerometry has been
53
54 proposed^{22;23;40} to improve the estimation of PAEE by accounting for some of the inter-individual
55
56 variance in the energy cost of MVPA. These differences, which may be due to individual traits such
57
58 as age, sex or aerobic fitness, are not fully reflected in accelerometers counts. Similarly, the
59
60

1
2
3 estimation of the energy cost of non-acceleration dependent activities which are frequent among
4 rural dwellers would be improved by incorporating HR data with acceleration. In our study, the
5
6 association between mean HRaS and PAEE measured by DLW was about six times stronger among
7
8 rural compared to urban subjects, suggesting that combining HR data with accelerometry should
9
10 improve the estimation of PAEE, particularly in the rural population.
11
12
13
14

15 Our results, in rural and urban SSA are comparable to a previous validation study in
16 Europe.⁴⁹ In a sample of 51 British adults (mean age of 34 years) using a step test calibration,
17 Brage⁴⁹ reported that the combined sensor had an accuracy (RMSE) of 25 kJ/kg/day and explained
18 34% of the variance in DLW-measured PAEE. This European population would be more
19 comparable to our urban sample (RMSE of 19 kJ/kg/day and explained variance of 30%) in terms of
20 types and pattern of activity. However, in contrast to our study which found no mean bias, the
21 European study reported a positive mean bias.⁴⁹ The European environment is much more urbanized
22 and mechanized than the urban areas in SSA, which may favour more acceleration-dependent
23 activities that are easily picked up by the accelerometer of the combined sensor.
24
25
26
27
28
29
30
31
32
33
34
35

36 Other validation studies in adults of this combined HR and movement sensor have been
37 carried out against indirect calorimetry during treadmill walking and running,⁵⁰ laboratory- or field-
38 based activities,^{51;52} or a 6-hour “free-living” activity.⁵³ The use of indirect calorimetry for free-
39 living monitoring may cause behaviour change or constraint and the activities undertaken would not
40 truly reflect real life. Also, the carefully controlled activities usually employed when evaluating the
41 validity of any activity monitor in the laboratory are not a true reflection of the lifestyle and patterns
42 of activities in free-living individuals. However, these studies all demonstrate the improved accuracy
43 of the combined sensor in estimating the energy expenditure of activities and the potential for use in
44 epidemiological studies.
45
46
47
48
49
50
51
52
53
54
55
56

57 A challenge to the use of HR monitoring in free-living individuals is the issue of missing or
58 noisy data. HR monitors pick up and register the electrical signals generated by the electrical system
59
60

1
2
3 of the heart during each heart beat. These monitors are susceptible to interferences from electrical
4 appliances or other sources of static current. Furthermore, the Actiheart unit clips on the chest using
5 standard ECG electrodes which need good skin contact for optimal signal detection. These
6 electrodes may become loose resulting in noisy or loss of signal detection. This was a problem in our
7 study since the tropical climate is usually warm and humid, and so the electrodes lose contact easily
8 due to profuse sweating during habitual daily activities. The problem of noisy or missing HR data is
9 resolved, in part, by the use of a cleaning and recovery or interpolation algorithm
10 (www.camntech.com). Additionally, the use of a branched equation modelling approach⁴⁰ enables
11 the prediction of PAEE to be based mainly on acceleration when the HR data cannot be recovered.
12
13
14
15
16
17
18
19
20
21
22
23

24 The small sample size of this validation study is another potential limitation in terms of
25 power to make valid inferences. This was principally due to the high cost of DLW measurements.
26 However, the high accuracy and precision of the DLW methods compensates for the small sample.
27
28
29
30

31 SSA is undergoing a rapid epidemiologic transition characterized by increasing prevalence of
32 obesity, diabetes and CVD.⁵⁴⁻⁵⁷ Urbanization resulting in lifestyle modification, with the adoption of
33 more sedentary behaviour and less physical activity, has been suggested as part of the behavioural
34 risk factors driving this transition. It is therefore important to objectively quantify this exposure in
35 order to more appropriately inform and guide policy or interventions. The results from this study
36 suggest that combined HR and movement sensing is a feasible and valid method which can be used
37 in epidemiologic studies to accurately assess free-living physical activity in this region.
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

KEY MESSAGES

- The increasing burden of non-communicable diseases in sub-Saharan Africa warrants rigorous studies of contributing lifestyle factors. However, the validity of objective measures of free-living physical activity in this region is scarce.
- This study showed that combined HR and movement sensing was a valid and accurate method of objectively measuring PAEE in free-living adult populations in rural and urban areas.
- PAEE estimated from combined HR and movement sensing was more accurate and valid compared to either HR or accelerometry alone.
- Individual calibration of HR response to exercise improved the validity of PAEE estimated by the combined sensor compared to the use of group equations.

Only

Acknowledgements

We are grateful to Anita Bukong, Mary Mbiatem, Christian Afuh and Kingsley Ngwa who assisted in data collection; and to Paul Roberts, Matt Sims and Kate Westgate who assisted in study coordination.

Funding

This work was supported by the Wellcome Trust (Grant GR074786MA) and the Medical Research Council Epidemiology Unit. FKA was supported by a Wellcome Trust Masters Training Fellowship and a Gates Cambridge Scholar Award with an Overseas Research Scheme Award.

Conflict of interest

None of the authors had any conflict of interest associated with this manuscript.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Review Only

References

- 1 Hu FB, Willett WC, Li T, Stampfer MJ, Colditz GA, Manson JE. Adiposity as compared with physical activity in predicting mortality among women. *N Engl J Med* 2004; **351**:2694-703.
- 2 Khaw KT, Jakes R, Bingham S *et al.* Work and leisure time physical activity assessed using a simple, pragmatic, validated questionnaire and incident cardiovascular disease and all-cause mortality in men and women: The European Prospective Investigation into Cancer in Norfolk prospective population study. *Int J Epidemiol* 2006; **35**:1034-43.
- 3 Manson JE, Greenland P, LaCroix AZ *et al.* Walking compared with vigorous exercise for the prevention of cardiovascular events in women. *N Engl J Med* 2002; **347**:716-25.
- 4 Hu G, Tuomilehto J, Silventoinen K, Barengo NC, Peltonen M, Jousilahti P. The effects of physical activity and body mass index on cardiovascular, cancer and all-cause mortality among 47 212 middle-aged Finnish men and women. *Int J Obes* 2005; **29**:894-902.
- 5 Department of Health. At least five a week: Evidence on the impact of physical activity and its relationship to health. A report from the Chief Medical Officer. 29-4-2004. London, Department of Health.
- 6 U.S.Department of Health and Human Services. *Physical Activity and Health: A Report of the Surgeon General.* 1996. Atlanta, GA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, 1996.
- 7 Blair SN, Kampert JB, Kohl HW, III *et al.* Influences of cardiorespiratory fitness and other precursors on cardiovascular disease and all-cause mortality in men and women. *JAMA* 1996; **276**:205-10.

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- 8 Davey Smith G, Shipley MJ, Batty GD, Morris JN, Marmot M. Physical activity and cause-specific mortality in the Whitehall study. *Public Health* 2000; **114**:308-15.
- 9 Wareham NJ, Rennie KL. The assessment of physical activity in individuals and populations: why try to be more precise about how physical activity is assessed? *Int J Obes Relat Metab Disord* 1998; **22**:S30-S38.
- 10 Westerterp KR. Assessment of physical activity: a critical appraisal. *Eur J Appl Physiol* 2009; **105**:823-8.
- 11 Hawkins MS, Storti KL, Richardson CR *et al*. Objectively measured physical activity of USA adults by sex, age, and racial/ethnic groups: a cross-sectional study. *Int J Behav Nutr Phys Act* 2009; **6**:31.
- 12 Hagstromer M, Oja P, Sjostrom M. Physical activity and inactivity in an adult population assessed by accelerometry. *Med Sci Sports Exerc* 2007; **39**:1502-8.
- 13 Troiano RP, Berrigan D, Dodd KW, Masse LC, Tilert T, McDowell M. Physical activity in the United States measured by accelerometer. *Med Sci Sports Exerc* 2008; **40**:181-8.
- 14 Neilson HK, Robson PJ, Friedenreich CM, Csizmadi I. Estimating activity energy expenditure: how valid are physical activity questionnaires? *Am J Clin Nutr* 2008; **87**:279-91.
- 15 Kurtze N, Rangun V, Hustvedt BE. Reliability and validity of the international physical activity questionnaire in the Nord-Trondelag health study (HUNT) population of men. *BMC Med Res Methodol* 2008; **8**:63.
- 16 Black AE, Cole TJ. Within- and between-subject variation in energy expenditure measured by the doubly-labelled water technique: implications for validating reported dietary energy intake. *Eur J Clin Nutr* 2000; **54**:386-94.
- 17 Prentice AM, Black AE, Coward WA, Cole TJ. Energy expenditure in overweight and obese adults in affluent societies: an analysis of 319 doubly-labelled water measurements. *Eur J Clin Nutr* 1996; **50**:93-7.

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- 18 Livingstone MB, Prentice AM, Coward WA *et al.* Simultaneous measurement of free-living energy expenditure by the doubly labeled water method and heart-rate monitoring. *Am J Clin Nutr* 1990; **52**:59-65.
- 19 Matthew CE. Calibration of accelerometer output for adults. *Med Sci Sports Exerc* 2005; **37**:S512-S522.
- 20 Trost SG, McIver KL, Pate RR. Conducting accelerometer-based activity assessments in field-based research. *Med Sci Sports Exerc* 2005; **37**:S531-S543.
- 21 Ceasay SM, Prentice AM, Day KC *et al.* The use of heart rate monitoring in the estimation of energy expenditure: a validation study using indirect whole-body calorimetry. *Br J Nutr* 1989; **61**:175-86.
- 22 Avons P, Garthwaite P, Davies HL, Murgatroyd PR, James WP. Approaches to estimating physical activity in the community: calorimetric validation of actometers and heart rate monitoring. *Eur J Clin Nutr* 1988; **42**:185-96.
- 23 Rennie K, Rowsell T, Jebb SA, Holburn D, Wareham NJ. A combined heart rate and movement sensor: proof of concept and preliminary testing study. *Eur J Clin Nutr* 2000; **54**:409-14.
- 24 Omran AR. The epidemiologic transition: a theory of the epidemiology of population change. 1971. *Milbank Q* 2005; **83**:731-57.
- 25 Popkin BM, Gordon-Larsen P. The nutrition transition: worldwide obesity dynamics and their determinants. *Int J Obes Relat Metab Disord* 2004; **28**:S2-S9.
- 26 Assah FK, Ekelund U, Brage S *et al.* Predicting physical activity energy expenditure using accelerometry in adults from sub-Saharan Africa. *Obesity* 2009; **17**:1588-95.
- 27 Leenders NY, Sherman WM, Nagaraja HN. Energy expenditure estimated by accelerometry and doubly labeled water: do they agree? *Med Sci Sports Exerc* 2006; **38**:2165-72.

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- 28 Keytel LR, Goedecke JH, Noakes TD *et al.* Prediction of energy expenditure from heart rate monitoring during submaximal exercise. *J Sports Sci* 2005; **23**:289-97.
- 29 Sobngwi E, Mbanya JCN, Unwin NC *et al.* Physical activity and its relationship with obesity, hypertension and diabetes in urban and rural Cameroon. *Int J Obes* 2002; **26**:1009-16.
- 30 St Onge MP, Rubiano F, Jones A, Jr., Heymsfield SB. A new hand-held indirect calorimeter to measure postprandial energy expenditure. *Obes Res* 2004; **12**:704-9.
- 31 Nieman DC, Trone GA, Austin MD. A new handheld device for measuring resting metabolic rate and oxygen consumption. *J Am Diet Assoc* 2003; **103**:588-92.
- 32 Weir JB. New methods for calculating metabolic rate with special reference to protein metabolism. *J Physiol* 1949; **109**:1-9.
- 33 Hoffman DJ, Sawaya AL, Coward WA *et al.* Energy expenditure of stunted and nonstunted boys and girls living in the shantytowns of Sao Paulo, Brazil. *Am J Clin Nutr* 2000; **72**:1025-31.
- 34 Coward WA. Stable isotopic methods for measuring energy expenditure. The doubly-labelled-water (2H₂(18)O) method: principles and practice. *Proc Nutr Soc* 1988; **47**:209-18.
- 35 Cole TJ, Coward WA. Precision and accuracy of doubly labeled water energy expenditure by multipoint and two-point methods. *Am J Physiol* 1992; **263**:E965-E973.
- 36 Schoeller DA, Ravussin E, Schutz Y, Acheson KJ, Baertschi P, Jequier E. Energy expenditure by doubly labeled water: validation in humans and proposed calculation. *Am J Physiol* 1986; **250**:R823-R830.
- 37 Elia M, Livesey G. Theory and validity of indirect calorimetry during net lipid synthesis. *Am J Clin Nutr* 1988; **47**:591-607.
- 38 Brage S, Brage N, Franks PW, Ekelund U, Wareham NJ. Reliability and validity of the combined heart rate and movement sensor Actiheart. *Eur J Clin Nutr* 2005; **59**:561-70.

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- 39 Brage S, Ekelund U, Brage N *et al.* Hierarchy of individual calibration levels for heart rate and accelerometry to measure physical activity. *J Appl Physiol* 2007; **103**:682-92.
- 40 Brage S, Brage N, Franks PW *et al.* Branched equation modeling of simultaneous accelerometry and heart rate monitoring improves estimate of directly measured physical activity energy expenditure. *J Appl Physiol* 2004; **96**:343-51.
- 41 Schofield WN. Predicting basal metabolic rate, new standards and review of previous work. *Hum Nutr Clin Nutr* 1985; **39**:S5-S41.
- 42 Bland JM, Altman DG. Statistical-Methods for Assessing Agreement Between 2 Methods of Clinical Measurement. *Lancet* 1986; **1**:307-10.
- 43 Cook RD. Detection of Influential Observation in Linear Regression. *Technometrics* 1977; **19**:15-8.
- 44 Mbalilaki JA, Hellenius ML, Masesa Z, Hostmark AT, Sundquist J, Stromme SB. Physical activity and blood lipids in rural and urban Tanzanians. *Nutr Metab Cardiovasc Dis* 2007; **17**:344-8.
- 45 Bassett DR, Jr., Ainsworth BE, Swartz AM, Strath SJ, O'Brien WL, King GA. Validity of four motion sensors in measuring moderate intensity physical activity. *Med Sci Sports Exerc* 2000; **32**:S471-S480.
- 46 Hendelman D, Miller K, Baggett C, Debold E, Freedson P. Validity of accelerometry for the assessment of moderate intensity physical activity in the field. *Med Sci Sports Exerc* 2000; **32**:S442-S449.
- 47 Welk GJ, Blair SN, Wood K, Jones S, Thompson RW. A comparative evaluation of three accelerometry-based physical activity monitors. *Med Sci Sports Exerc* 2000; **32**:S489-S497.
- 48 Wareham NJ, Hennings SJ, Prentice AM, Day NE. Feasibility of heart-rate monitoring to estimate total level and pattern of energy expenditure in a population-based epidemiological study: the Ely Young Cohort Feasibility Study 1994-5. *Br J Nutr* 1997; **78**:889-900.

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- 49 Soren Brage. Objective Monitoring of Physical Activity in the Epidemiological Setting Using Accelerometry and Heart Rate Monitoring. PhD Thesis, University of Cambridge; 2006.
- 50 Brage S, Brage N, Ekelund U *et al.* Effect of combined movement and heart rate monitor placement on physical activity estimates during treadmill locomotion and free-living. *Eur J Appl Physiol* 2006; **96**:517-24.
- 51 Crouter SE, Churilla JR, Bassett DR, Jr. Accuracy of the Actiheart for the assessment of energy expenditure in adults. *Eur J Clin Nutr* 2008; **62**:704-11.
- 52 Thompson D, Batterham AM, Bock S, Robson C, Stokes K. Assessment of low-to-moderate intensity physical activity thermogenesis in young adults using synchronized heart rate and accelerometry with branched-equation modeling. *J Nutr* 2006; **136**:1037-42.
- 53 Strath SJ, Brage S, Ekelund U. Integration of physiological and accelerometer data to improve physical activity assessment. *Med Sci Sports Exerc* 2005; **37**:S563-S571.
- 54 Mensah GA. Ischaemic heart disease in Africa. *Heart* 2008; **94**:836-43.
- 55 Kengne AP, Anderson CS. The neglected burden of stroke in Sub-Saharan Africa. *Int J Stroke* 2006; **1**:180-90.
- 56 Connor MD, Walker R, Modi G, Warlow CP. Burden of stroke in black populations in sub-Saharan Africa. *Lancet Neurol* 2007; **6**:269-78.
- 57 Mbanya JC, Kengne AP, Assah F. Diabetes care in Africa. *Lancet* 2006; **368**:1628-9.

Table 1. Descriptive Characteristics of Study Participants, Actiheart Free-living Validation in sub-Saharan Africa Study, Cameroon, 2006.

	All	Rural	Urban	<i>P</i>
Sex (M/F)	16/17	8/9	8/8	
Age (years)	34.2 (7.3)	35.4 (6.8)	33.0 (7.8)	0.3
BMI (kg/m ²)	27.1 (4.6)	27.8 (4.7)	26.25 (4.6)	0.3
TEE from DLW (MJ/day)	12.44 (3.53)	13.13 (4.16)	11.71 (2.64)	0.3
PAEE from DLW (kJ/kg/day)	58.2 (31.0)	65.7 (36.5)	50.2 (22.1)	0.2
PAL from DLW	1.79 (0.37)	1.89 (0.45)	1.68 (0.23)	0.1
PAEE from Actiheart ^a (kJ/kg/day)				
ACC+HR _{STEP}	52.8 (19.4)	56.6 (20.8)	48.7 (17.5)	0.2
ACC+HR _{GROUP}	49.1 (17.3)	50.1 (18.8)	48.0 (16.1)	0.7
HR _{FLEX}	59.4 (30.3)	63.4 (33.4)	55.2 (27.1)	0.4
ACC	31.6 (10.0)	33.3 (9.4)	29.8 (10.6)	0.3
Mean Acceleration (m/s ²)	0.112 (0.049)	0.117 (0.049)	0.107 (0.05)	0.6
Mean HRaS (beats/min)	16.2 (4.1)	17.0 (3.6)	15.4 (4.5)	0.3
Sedentary time (minutes/day)	988 (136)	954 (143)	1024 (122)	0.1
LPA (minutes/day)	319 (100)	334 (96)	303 (104)	0.4
MVPA (minutes/day)	133 (58)	152 (64)	113 (45)	0.05

Abbreviations: BMI, body mass index; DLW, doubly labelled water; HRaS, heart rate above sleeping heart rate; LPA, light intensity physical activity; MVPA, moderate-to-vigorous intensity physical activity; PAEE, physical activity energy expenditure; PAL, physical activity level; TEE, total energy expenditure.

1
2
3 Data are means (SD). *P* value for difference between rural and urban groups.
4

5 ^aModels of PAEE prediction from Actiheart: ACC=group acceleration equation; HR_{STEP}=individual
6 step test calibration of heart rate; HR_{GROUP}=group heart rate calibration; HR_{FLEX}=individual step test
7 calibration with PAEE prediction based only on flex HR method.
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Review Only

Table 2. Correlations Between PAEE (kJ/kg/day) Measured by DLW and Parameters Derived From Heart Rate and Movement Monitoring in Free-living Healthy Adults, Actiheart Free-living Validation in sub-Saharan Africa Study, Cameroon, 2006.

	PAEE from DLW (kJ/kg/day)					
	All (n=33)		Rural (n=17)		Urban (n=16)	
	R	P	r	P	r	P
PAEE from Actiheart ^a (kJ/kg/day)						
ACC+HR _{STEP}	0.40	0.02	0.29	0.3	0.55	0.03
ACC+HR _{GROUP}	0.39	0.02	0.34	0.2	0.51	0.04
HR _{FLEX}	0.32	0.07	0.25	0.3	0.40	0.1
ACC	0.54	0.001	0.45	0.07	0.70	0.002
Mean Acceleration	0.54	0.001	0.48	0.05	0.66	0.01
Mean HRaS (beats/min)	0.23	0.2	0.31	0.2	0.05	0.8
Sedentary time (minutes/day)	-0.43	0.01	-0.33	0.2	-0.54	0.03
LPA (minutes/day)	0.37	0.03	0.28	0.3	0.49	0.05
MVPA (minutes/day)	0.37	0.03	0.31	0.2	0.34	0.2

Abbreviations: DLW, doubly-labelled water; PAEE, physical activity energy expenditure; HRaS, heart rate above sleeping heart rate; LPA, light intensity physical activity; MVPA, moderate-to-vigorous intensity physical activity.

^aModels of PAEE prediction from Actiheart: ACC=group acceleration equation;

HR_{STEP}=individual step test calibration of heart rate; HR_{GROUP}=group heart rate

calibration; HR_{FLEX}=individual step test calibration with PAEE prediction based only on

flex HR method.

For Review Only

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Table 3. Criterion Validity of PAEE Derived From Combined Heart Rate and Movement Monitoring and Measured by DLW in Free-living Healthy Adults, Actiheart Free-living Validation in sub-Saharan Africa Study, Cameroon, 2006.

Model	PAEE	Bias ^a	<i>P</i> for bias	RMSE	95% LOA
Criterion method					
DLW	58.2 (31.0)				
Heart rate and movement models^b					
ACC + HR _{STEP}	52.8 (19.4)	-5.4 (5.1)	0.3	29.3	-62.7, 51.9
Rural	56.6 (20.8)	-9.1 (8.9)	0.32	36.5	-80.6, 62.4
Urban	48.7 (17.5)	-1.4 (4.8)	0.77	18.7	-39.3, 36.4
ACC + HR _{GROUP}	49.1 (17.3)	-9.1 (5.0)	0.08	29.9	-65.8, 47.6
Rural	50.1 (18.8)	-15.6 (8.5)	0.08	37.3	-84.1, 52.9
Urban	48.0 (16.1)	-2.2 (4.9)	0.66	19.2	-40.8, 36.3
HR _{FLEX}	59.4 (30.3)	1.2 (6.2)	0.85	35.2	-68.9, 71.3
Rural	63.4 (33.4)	-2.4 (10.4)	0.82	41.4	-86.3, 81.5
Urban	55.2 (27.1)	5.0 (8.8)	0.47	26.9	-48.4, 58.5
ACC	31.6 (10.0)	-26.6 (4.7)	<0.001	37.5	-79.3, 26.1
Rural	33.3 (9.4)	-32.5 (8.1)	0.003	45.9	-97.9, 33.0
Urban	29.8 (10.6)	-20.4 (4.1)	0.001	25.9	-52.7, 12.0

Abbreviations: DLW, doubly-labelled water; LOA, limits of agreement; PAEE, physical activity energy expenditure; RMSE, root mean square error

Units of all data are (kJ/kg/day). Values of PAEE are mean (SD), bias are means (SE).

^aMean bias = predicted – criterion.

1
2
3 ^bModels of PAEE prediction from Actiheart: ACC=group acceleration equation;
4

5
6 HR_{STEP}=individual step test calibration of heart rate; HR_{GROUP}=group heart rate calibration;
7

8 HR_{FLEX}=individual step test calibration with PAEE prediction based only on flex HR method.
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

For Review Only

Individual HR calibration (ACC + HR_{STEP})

Group HR calibration (ACC + HR_{GROUP})

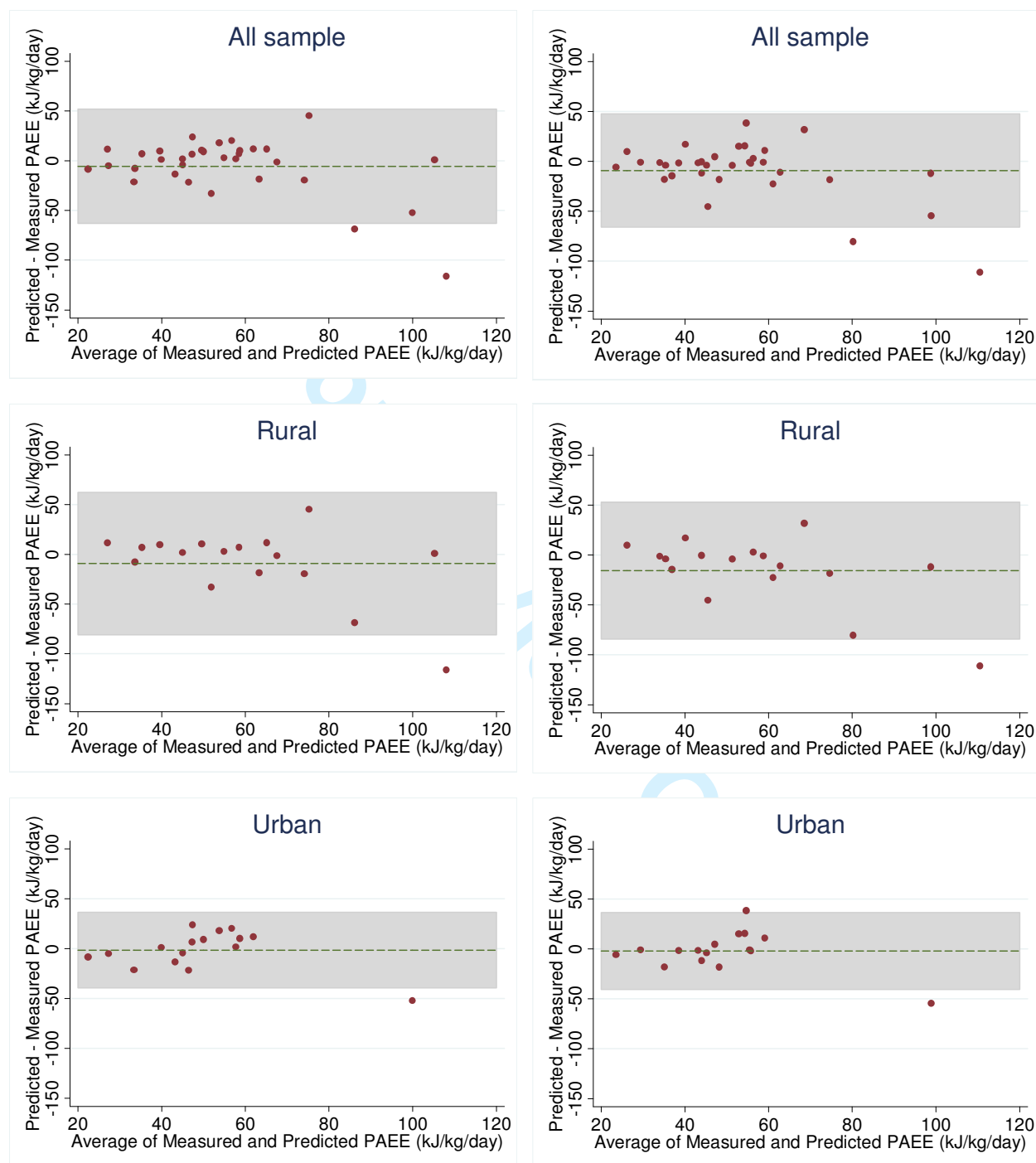


Figure 1. Bland and Altman Plots of the Difference Versus the Mean of PAEE Measured by Doubly-labelled Water and Derived From Combined Heart Rate and Movement Monitoring in Healthy Adults, Actiheart Free-living Validation in sub-Saharan Africa Study, Cameroon, 2006. Abbreviations: ACC, acceleration; PAEE, physical activity energy expenditure; HR, heart rate.