

Assessment of Physical Activity and relation to Diabetes traits

Søren Brage
MRC Epidemiology Unit
University of Cambridge, UK

soren.brage@mrc-epid.cam.ac.uk

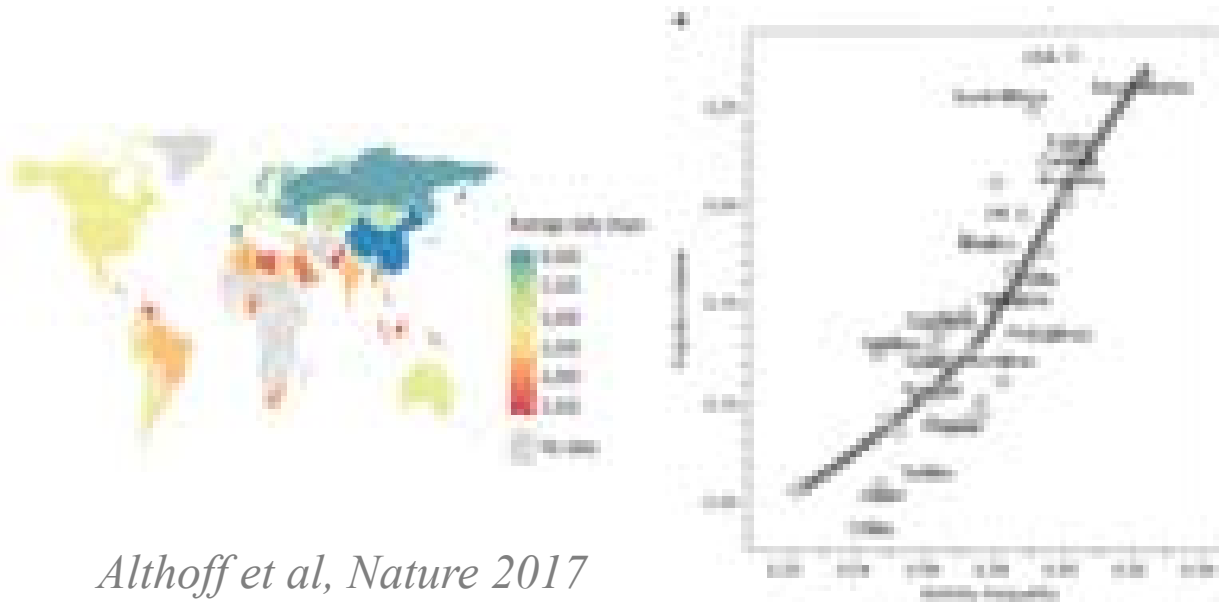
Smartphone-measures of physical activity

Large-scale physical activity data reveal worldwide activity inequality

Tim Althoff¹, Rob Smith², Jennifer L. Hicks³, Abby C. Kling^{1,4}, Scott L. Delp^{1,3} & Jane Lindemann^{1,3}

N = 717,000 (68M person-days)

App counts steps (iPhone users)



- Big Data = epi ?
- Reliability ?
- Validity ?
- Within-person selection bias ?
- Sample selection bias ?

Althoff et al, Nature 2017

Total Daily Energy Expenditure

Thermic effect of feeding
(Food intake; cold stress;
thermogenic drugs)

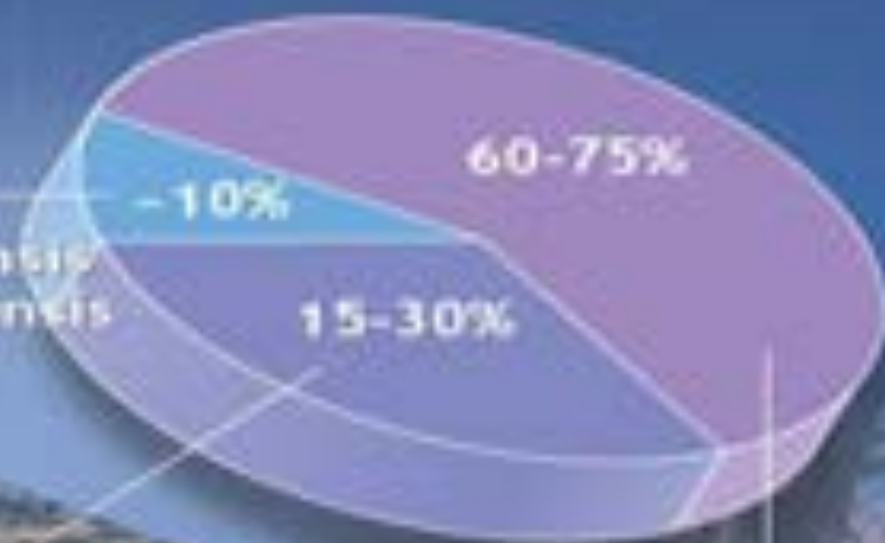
- Obligatory thermogenesis
- Facultative thermogenesis

**Thermic effect
of physical activity**
(Duration and intensity)

- In occupation
- In home
- In sport and recreation

Resting metabolic rate
(Fat-free body mass;
Gender; thyroid hormones;
protein turnover)

- Sleeping metabolism
- Basal metabolism
- Arousal metabolism

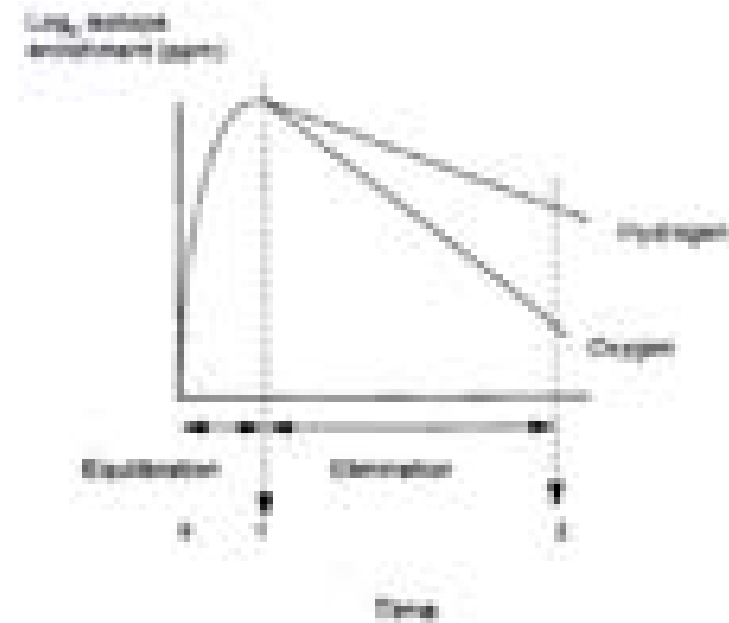


The Doubly Labelled Water (DLW) Method

Gold standard for assessment of TEE in real-life situations

Principle:

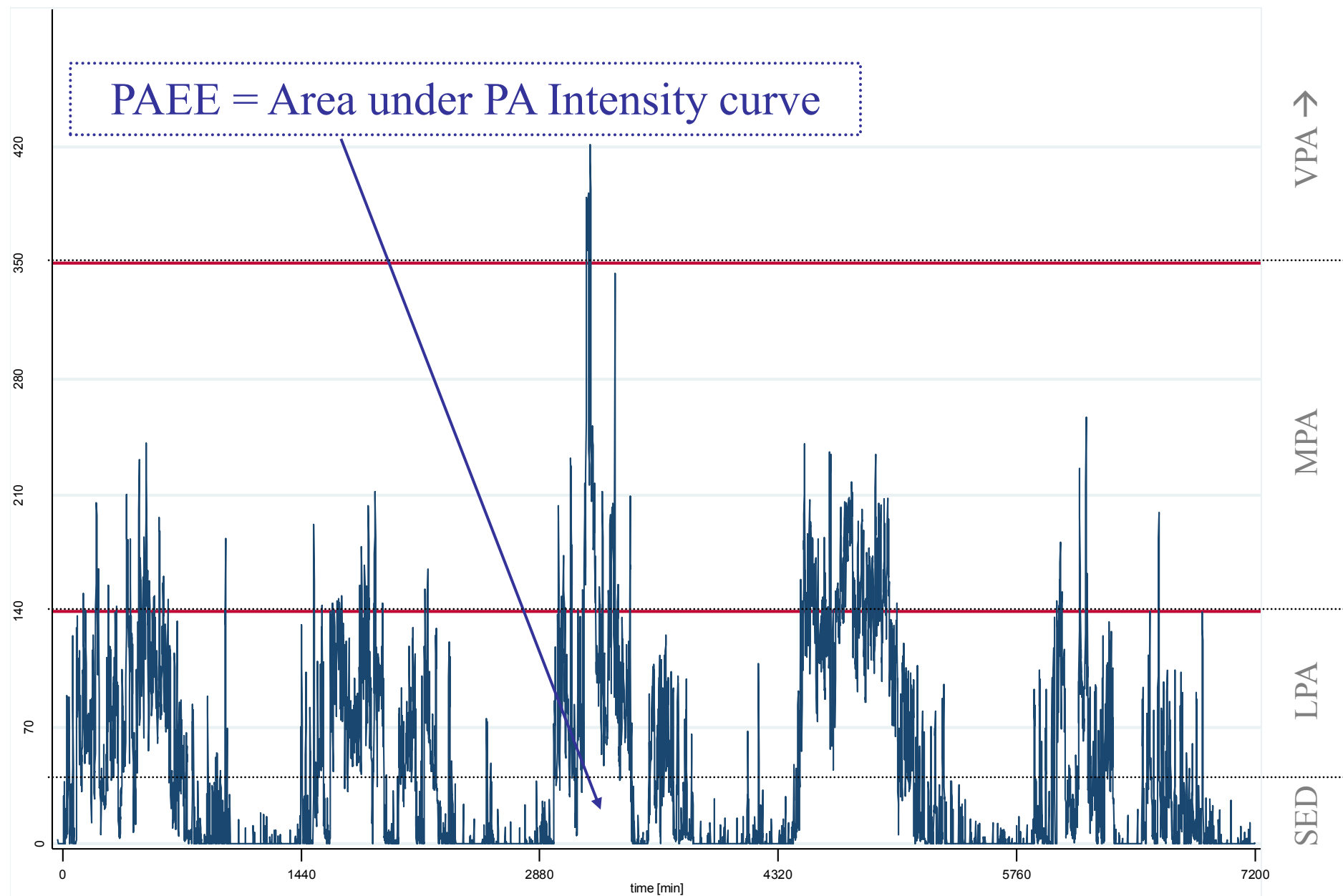
- Stable isotopes (^2H and ^{18}O) are drunk as water
- Equilibrate with body water (after several hours)
- ^2H is eliminated from the body as water
- ^{18}O is eliminated both as water and as CO_2
- The difference in elimination rates provides a **measure of CO_2 production** and therefore of TEE (over 10-14 days)
- No information on patterns, eg. intensity
- ~750 GBP per measurement (adults)



Dimensions of physical activity

- **Type**
 - The type or mode of activity refers to the different specific activities a person is engaged in (e.g. standing, walking, cycling, load bearing, etc)
- **Frequency**
 - Number of activity bouts during a specific time period
- **Duration**
 - Time (sec, min, hours) of participation in a single bout of activity
- **Intensity**
 - The physiological or biomechanical effort per unit time associated with participating in a specific type of activity
- **Volume**
 - The integrated product of the above!
- **Domains / settings**
 - Leisure / occupational / transport
 - Social context (alone / with peers / with others)
 - Spatial (in-doors or out, green space, perceived safe, etc.)

Intensity time-series during free-living



Methodologies

Subjective (individual):

- Interviews
- Questionnaires
- Diaries / activity logs
- Proxy-reports
- And... _____ ?

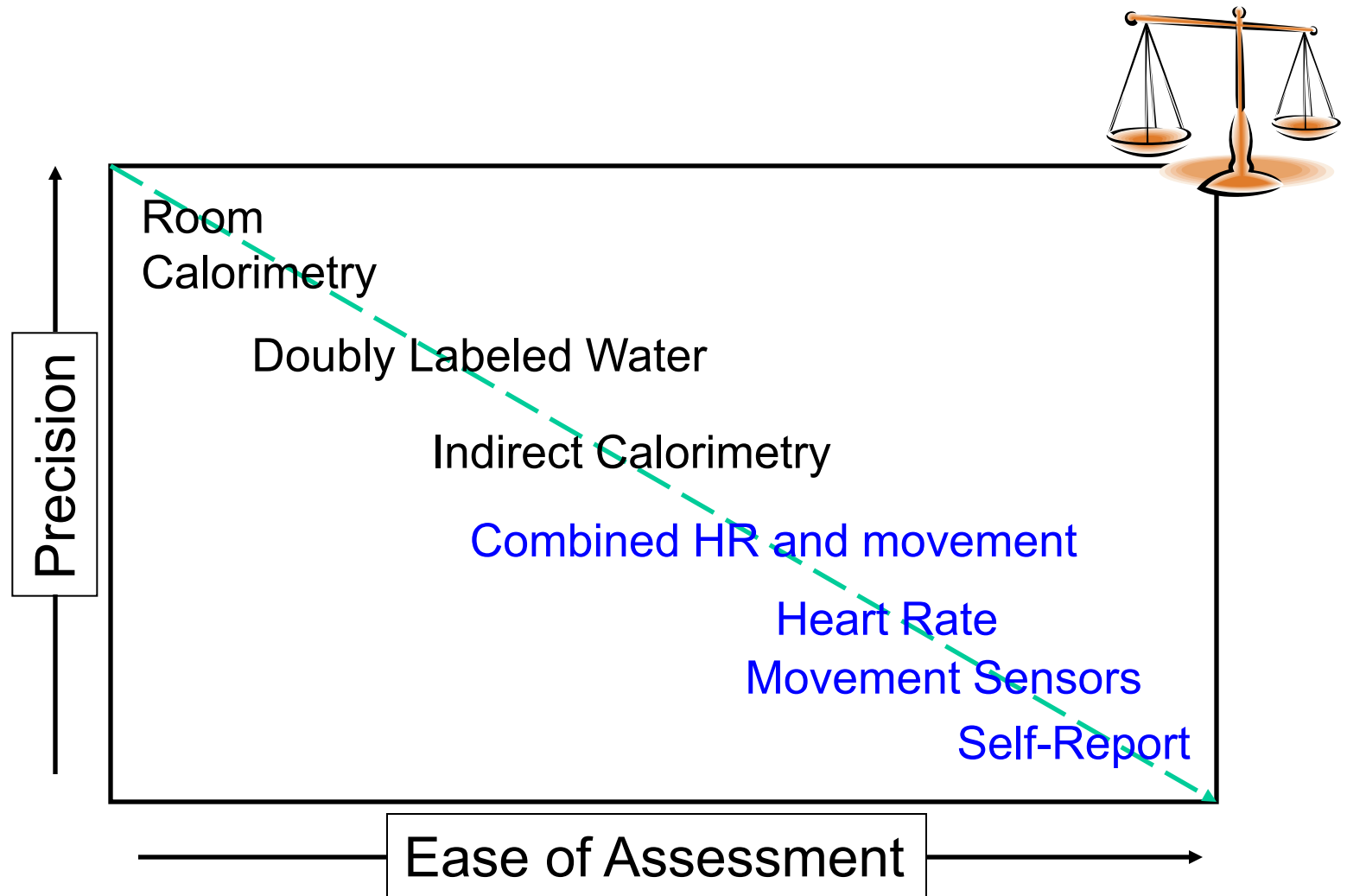
Non-individual:

- # cars / household
- # bikes / university
- 'CCTV walk density'
- Google Street View
- Proximity sensors
- And..._____ ?

Objective (individual):

- Direct observation
- Pedometry
- Accelerometry
- Gyroscopy
- Heart rate monitoring
- GPS, other location systems
- Galvanic skin response
- Heat flux
- Doubly-labeled Water
- VO₂ / VCO₂
- Calorimetry
- "Smartphone apps"
- And..._____ ?

Measuring Physical Activity: Validity vs feasibility



Methodological advances shifts the balance



A Volunteer Sitting with His Arms in Saline-Filled Tubes with Wires Connected to Einthoven's Electrocardiograph.

BMJ | Medical Research Council



Method: Measurement + Inference = Estimate

<u>Measurement method</u>		<u>Measured signal</u>		<u>Estimate</u>
Room Calorimetry	————→	Heat (or CO ₂ and VO ₂)→	TEE → PAEE
Doubly Labeled Water	————→	CO ₂→	TEE → PAEE
Indirect Calorimetry	————→	CO ₂ and VO ₂→	TEE → PAEE
Accelerometry	————→	Acceleration→	(counts) → PAEE
Heart Rate Monitoring	————→	ECG, HR→	PAEE
Self-Report	————→	Memory! (time in behavior)→	PAEE

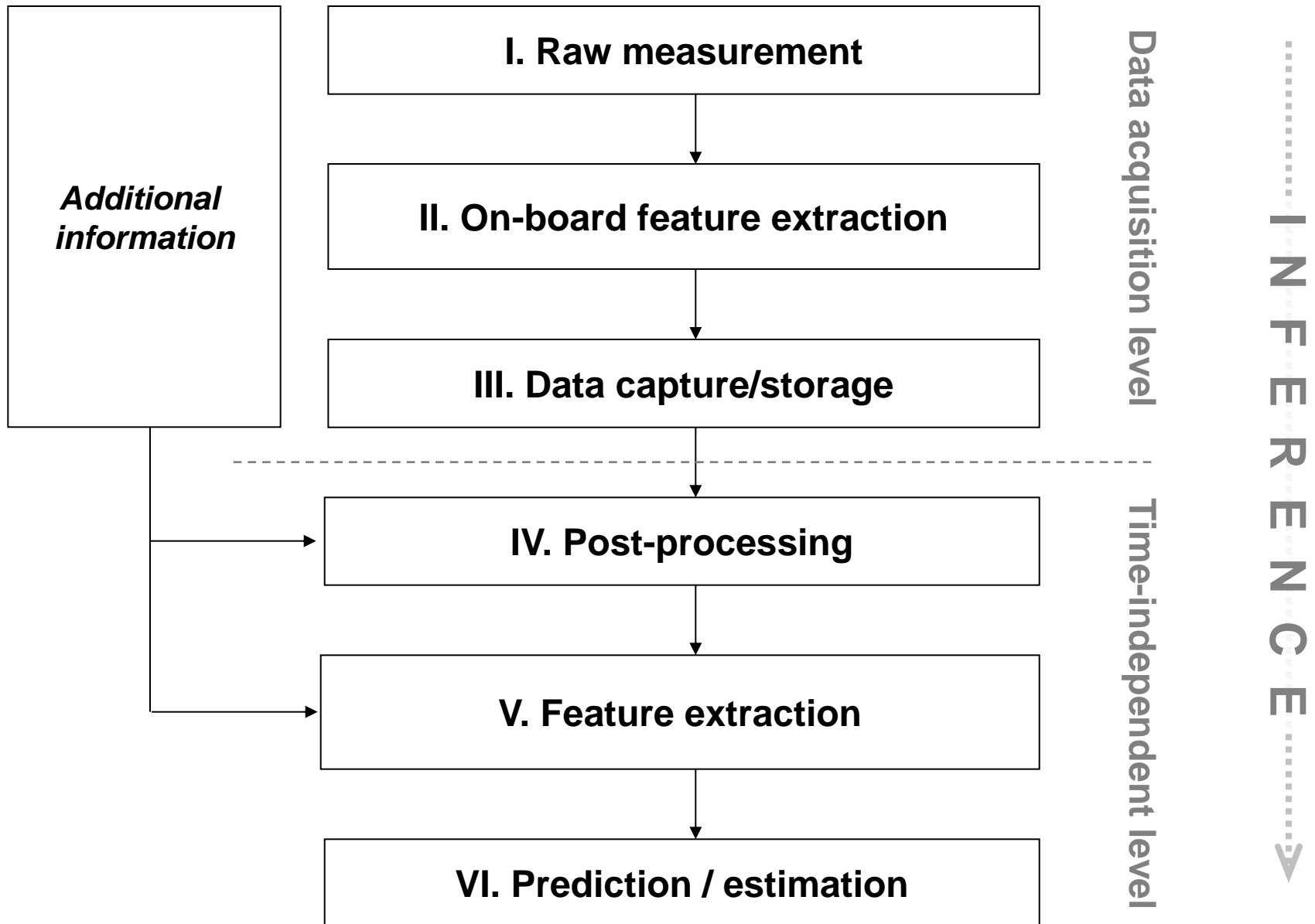


Validity is determined by...

- *what is being measured*
- *what is being estimated and how*

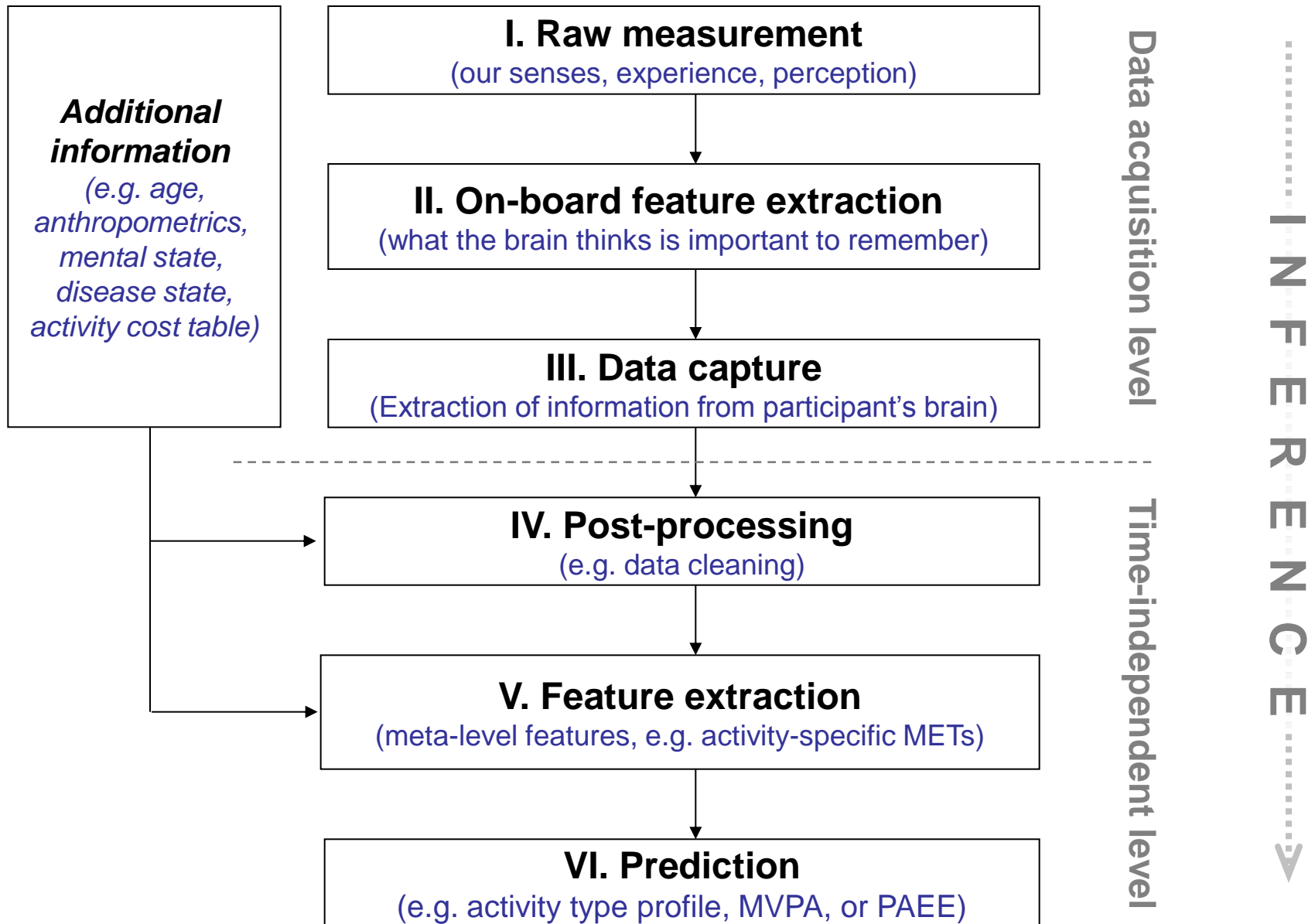
"Inference is everything"





Questionnaires

- Subjective measure of activity
- Relies on the **responses** from the person under investigation
- Time frame: 24-hr recall, week(s), 1 year, lifetime
- Self administered or interview based
- *Typical summary estimates:*
 - PAEE (total and by domain)
 - Time spent in intensity categories
 - Time spent in specific activities



Computation of estimates of physical activity EE from questionnaires

Frequency x Duration x Intensity x Body weight

2 events/week x 1.5 hr/event x 6 METs x 70 kg

↙
Time

3 hr/week

↘
Energy expended

18 MET-hr/week (18 kcal/kg/week)

↘
Energy expended
1260 kcal/week

Physical activity and incidence of NIDDM

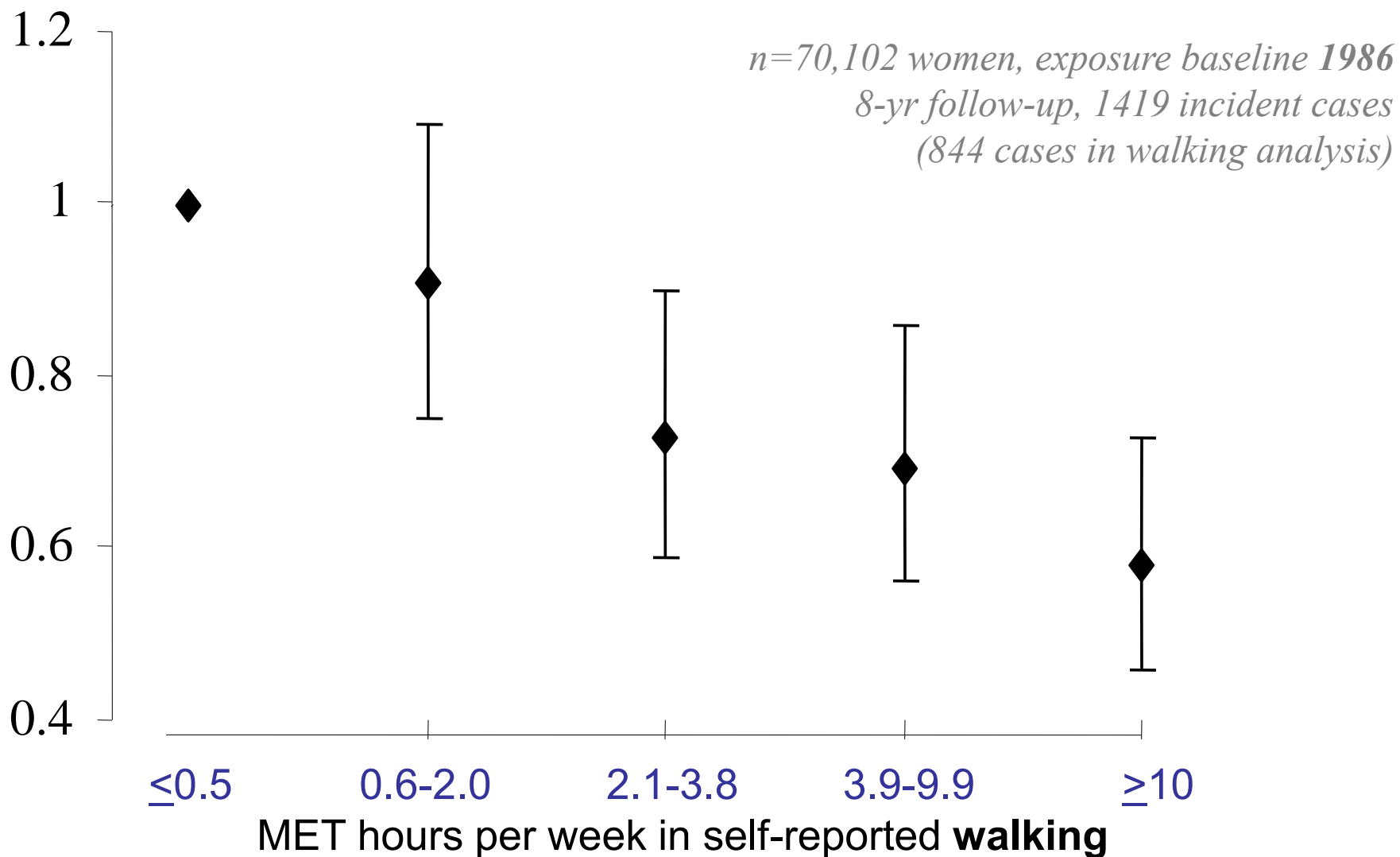
Nurses' Health Study

Vigorous activity <i>(episodes per week)</i>	RR <i>age adjusted</i>	RR <i>age & BMI adjusted</i>
0	1	1
1	0.74 (0.60-0.91)	0.89 (0.72-1.11)
2	0.55 (0.44-0.68)	0.71 (0.56-0.89)
3	0.73 (0.59-0.90)	0.93 (0.73-1.16)
4+	0.63 (0.53-0.75)	0.86 (0.71-1.04)
at least once weekly	0.67 (0.60-0.75)	0.84 (0.75-0.95)

n=87,253 women, 34-53 yrs, exposure baseline 1980
8-yr follow-up, 1303 incident cases

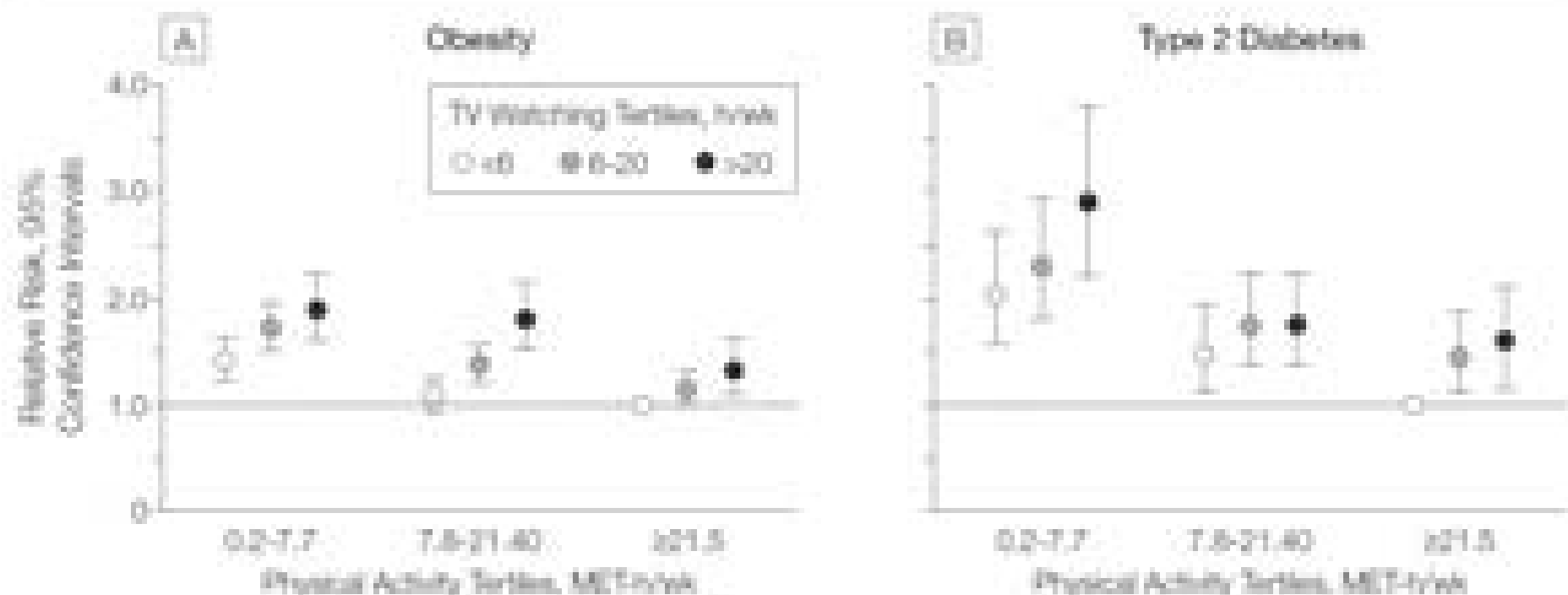
Manson et al, Lancet 1991

RR of T2DM among women who did **not** report vigorous activity



Combined effects of physical activity and sedentary behaviour

Figure 2. Relative Risks of Developing Obesity Among Nonobese Women and of Developing Type 2 Diabetes Among Nondiabetic Women According to Joint Classification of Physical Activity Levels (Metabolic Equivalent Hours/Wk [MET-h/wk]) and Time Spent Watching Television (TV)



T2DM analysis:

n=68,497 women, exposure baseline 1992

6-yr follow-up, 1515 incident cases

Hu et al, JAMA 2003

Critical appraisal: Metabolic Equivalent Task (MET)

	Activity A	Activity B	Ratio (B/A)
Intensity			
VO ₂ (ml O ₂ /min/kg)	7.0	14.0	2.0
Standard MET	2	4	2.0
Marginal MET	1	3	3.0
PAEE (J/min/kg)	70	210	3.0

Q: How do activities A and B equate?

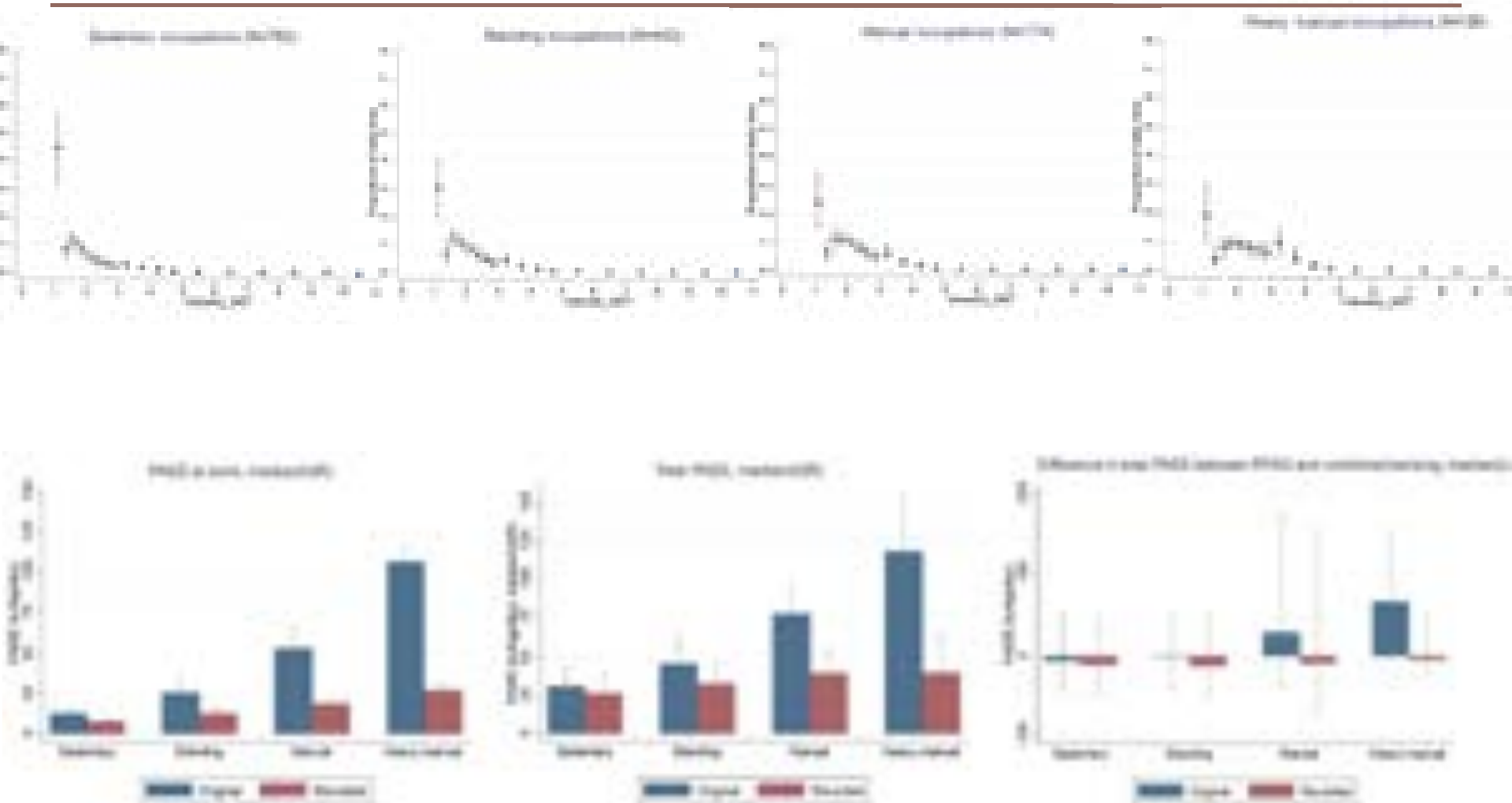
1 standard MET = 3.5 ml O₂/min/kg

1 ml O₂ ~ 20 J

Exposing our PAQ assumptions:



Intensity distribution of working hours



Physical activity in EPIC Europe

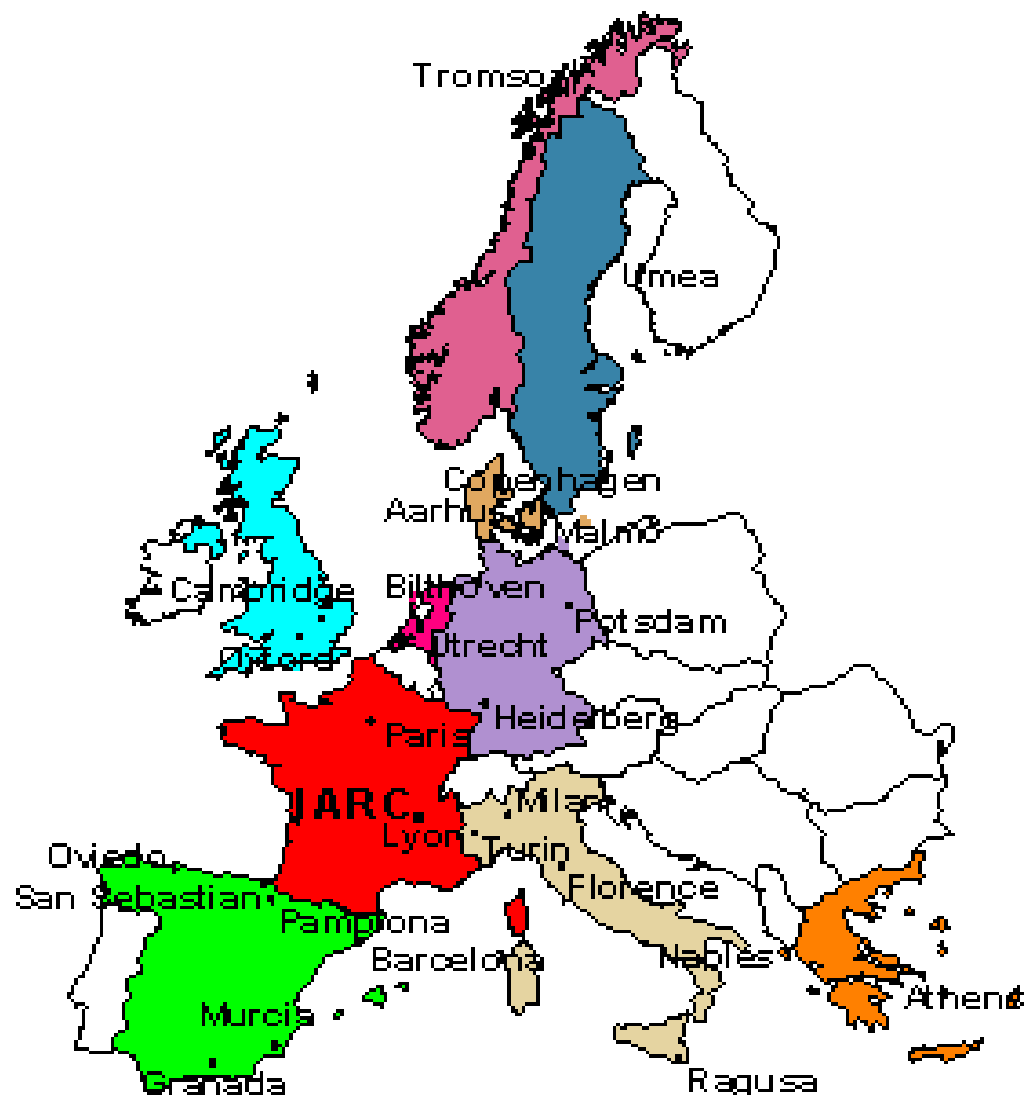
Time frame: Past year

- **Work category**

Sedentary, Standing, Manual,
Heavy manual

- **Leisure time:**

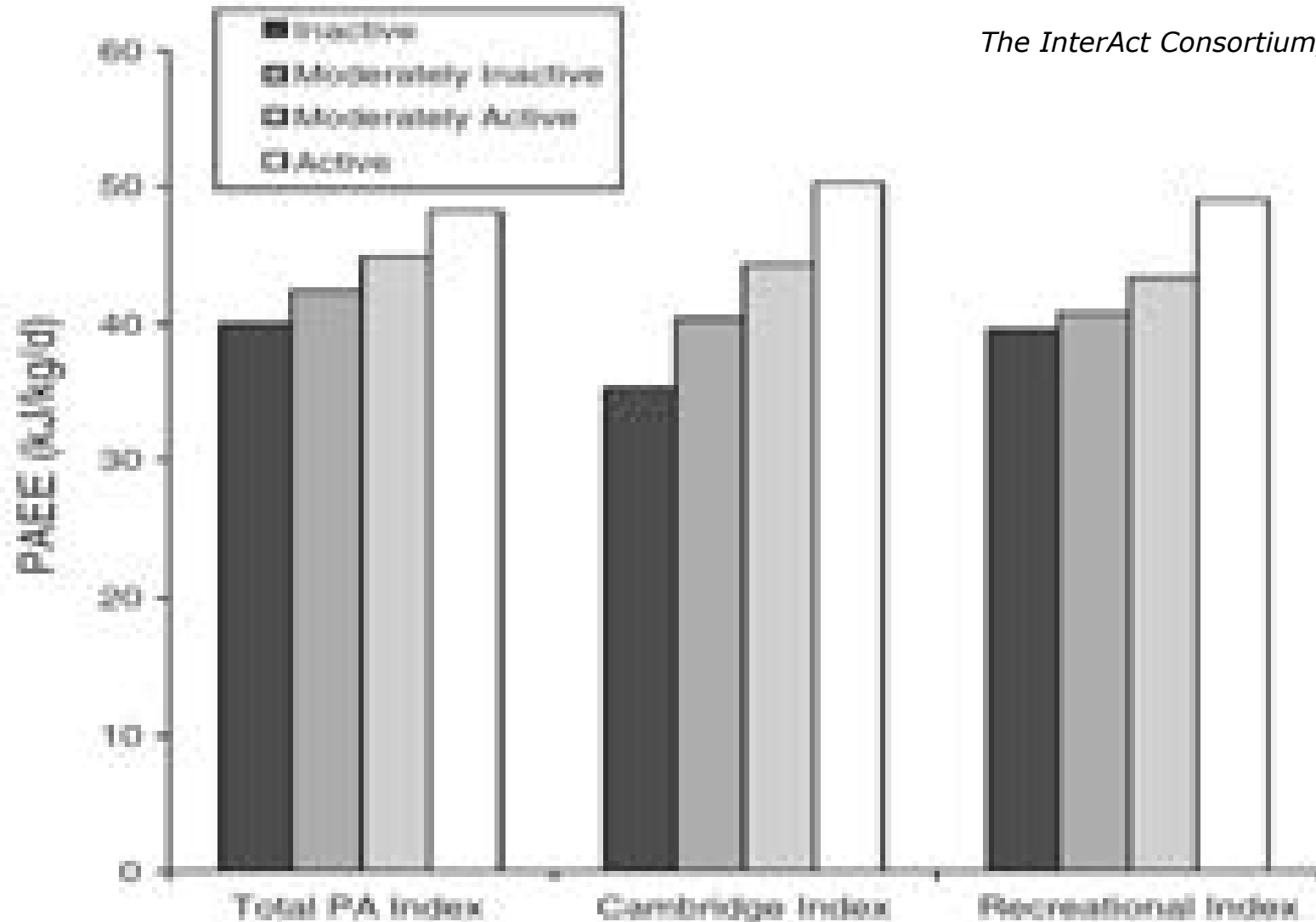
Walking, Cycling, Gardening,
DIY, Physical exercise,
Housework



Derived PA index ("Cambridge index")

Work activity	Leisure time physical activity (Duration of sport and cycling in hrs/wk)			
	No	≤ 3.5	> 3.5 and ≤ 7.0	> 7.0
Sedentary	Inactive	Moderately inactive	Moderately active	Active
Standing	Moderately inactive	Moderately active	Active	Active
Manual	Moderately active	Active	Active	Active
Heavy manual	Active	Active	Active	Active

Country-specific validity of three indices of PA derived from short EPIC PAQ: *Acc+HR estimates of PAEE by category*



The InterAct Consortium, Eur J Epid 2012

Variable	95% CI (95% CrI)
Age	1.00 (0.99, 1.00)
Sex	0.99 (0.98, 1.00)
Education	0.97 (0.95, 0.99)
Knowledge	0.98 (0.97, 0.99)
Income	0.97 (0.95, 0.99)
Attitude	1.00 (0.99, 1.00)
Perceived barriers	0.99 (0.98, 0.99)
Perceived benefits	0.98 (0.97, 0.99)
Normative beliefs	0.99 (0.98, 0.99)
Self-efficacy	0.97 (0.95, 0.99)
Overall $\chi^2 = 49.97$, $p < 0.001$	0.97 (0.95, 0.99)

[illegible]

Country	95% CI (95% CrI)
Spain	0.00 (-0.00) 0.00
Spain	0.00 (-0.00) 0.00
Germany	0.00 (-0.00) 0.00
Germany	0.00 (-0.00) 0.00
United	0.00 (-0.00) 0.00
Belgium	0.00 (-0.00) 0.00
Italy	0.00 (-0.00) 0.00
France	0.00 (-0.00) 0.00
Sweden	0.00 (-0.00) 0.00
Sum of 9/10 PRs, adjusted	0.00 (-0.00) 0.00

Country	with policy (%)
France	0.000 (0.000, 0.000)
Italy	0.000 (0.000, 0.000)
Spain	0.000 (0.000, 0.000)
Netherlands	0.000 (0.000, 0.000)
Germany	0.000 (0.000, 0.000)
Sweden	0.000 (0.000, 0.000)
Belgium	0.000 (0.000, 0.000)
Austria	0.000 (0.000, 0.000)
Portugal	0.000 (0.000, 0.000)
Finland	0.000 (0.000, 0.000)
Denmark	0.000 (0.000, 0.000)
United Kingdom	0.000 (0.000, 0.000)
Overall	0.000 (0.000, 0.000)
Overall (95% CI)	0.000 (0.000, 0.000)

Fig. 1 All-cause CVDs of incident diabetes, per one-level difference in physical activity (a) men and (b) women. Models are adjusted for baseline BMI, education, smoking status, alcohol consumption and energy intake

PA-T2DM: Effect modification by obesity?

Table 2 Continued effects (HR [95% CI]) of overall physical activity and BMI on incident diabetes in men (n=11,000) and women (n=11,000)

Variable	Activity category			
	Active	Moderately active	Moderately inactive	Inactive
Men				
n	3,648	3,764	3,490	3,099
Normal weight (BMI <25 kg/m ²)	1.00	0.85 (0.63, 1.16)	0.52 (0.38, 0.72)	1.00 (0.74, 1.40)
Overweight (BMI 25–30 kg/m ²)	1.00	1.00 (0.73, 1.38)	0.37 (0.26, 0.54)	1.30 (1.14, 1.47)
Obese (BMI ≥30 kg/m ²)	1.00	1.15 (0.87, 1.49)	0.36 (0.26, 0.51)	1.30 (1.08, 1.56)
Women				
n	3,438	3,134	3,428	4,070
Normal weight (BMI <25 kg/m ²)	1.00	1.12 (0.88, 1.43)	0.33 (0.24, 0.46)	1.50 (1.15, 1.95)
Overweight (BMI 25–30 kg/m ²)	1.00	1.17 (0.86, 1.60)	0.27 (0.19, 0.41)	1.40 (1.18, 1.72)
Obese (BMI ≥30 kg/m ²)	1.00	1.19 (0.91, 1.55)	0.27 (0.19, 0.40)	1.2 (0.94, 1.54)

n.s. →

Table 3 Continued effects of overall physical activity and overall obesity (BMI) on incident diabetes in men (n=10,740) and women (n=10,810)

Variable	Activity category			
	Active	Moderately active	Moderately inactive	Inactive
Men				
n	3,511	3,534	3,400	3,294
NO (≤74 mm)	1.00	0.11 (0.06, 0.19)	0.23 (0.16, 0.31)	0.44 (0.33, 0.57)
NO (≥74 mm)	1.00	0.85 (0.66, 1.21)	0.2 (0.14, 0.28)	0.38 (0.31, 0.47)
Women				
n	3,294	3,090	3,294	4,429
NO (≤80 mm)	1.00	0.06 (0.03, 0.10)	0.22 (0.16, 0.30)	0.29 (0.24, 0.35)
NO (≥80 mm)	1.00	0.17 (0.10, 0.28)	0.08 (0.05, 0.13)	0.18 (0.14, 0.24)

Values are HR [95% CI], unless specified otherwise

Models are adjusted for study location, education (none, primary, tertiary/other secondary), professionally working status (never, former, current), alcohol consumption (grams/day), energy intake (kilocalories/day) and BMI

PA, obesity, and diabetes in Korea

675,496 men

PA: Minutes of exercise “causing sweating”

52,995 incident cases

Table 1. Incident Cases of Diabetes Mellitus by Age, Sex, and Physical Activity Level in the Korean National Health and Nutrition Examination Survey, 1998-2007

Physical Activity Level*	Age (years)†											
	Young Adults (15-29)			Adults (30-49)			Middle-aged (50-69)			Older (≥70)		
	Total Participants	Men	Incidence (per 1000)	Total Participants	Men	Incidence (per 1000)	Total Participants	Men	Incidence (per 1000)	Total Participants	Men	Incidence (per 1000)
All	675,496	675,496	10.0	675,496	675,496	10.0	675,496	675,496	10.0	675,496	675,496	10.0
Low	100,000	100,000	12.0	100,000	100,000	12.0	100,000	100,000	12.0	100,000	100,000	12.0
Medium	200,000	200,000	8.0	200,000	200,000	8.0	200,000	200,000	8.0	200,000	200,000	8.0
High	375,496	375,496	5.0	375,496	375,496	5.0	375,496	375,496	5.0	375,496	375,496	5.0
Total	675,496	675,496	10.0	675,496	675,496	10.0	675,496	675,496	10.0	675,496	675,496	10.0

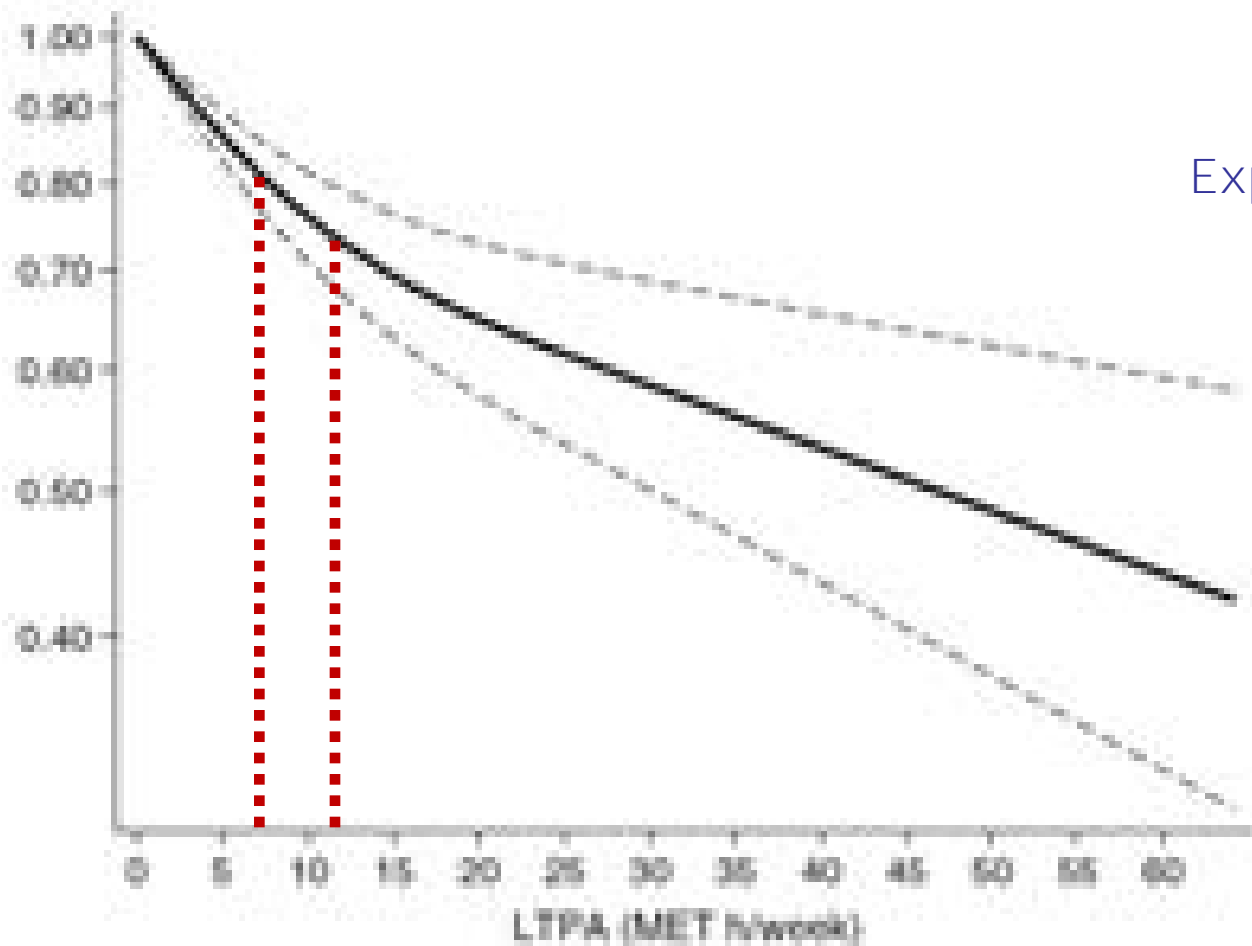
*Physical activity level: low, medium, high.

†The age groups were defined as young adults (15-29 years), adults (30-49 years), middle-aged (50-69 years), and older (≥70 years).

‡Incidence rates were age-adjusted.

Dose-response Meta-analysis: Leisure-time activity

28 studies
1.26 million people
84 k incident cases
Self-reported LTPA
Exposure harmonisation

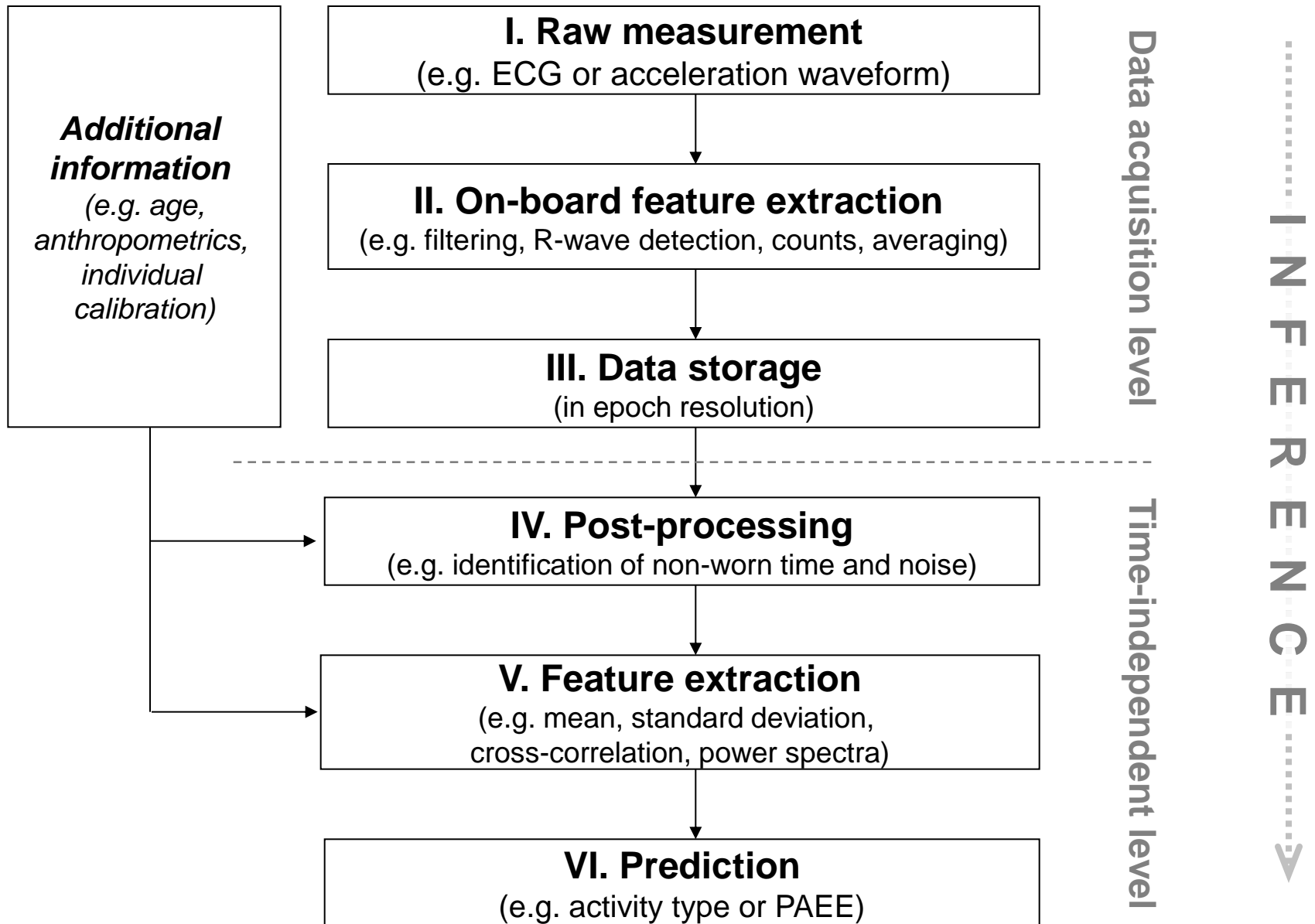


2.5 hrs/wk @ 3.0 METs = 7.50 MET-hrs/wk

2.5 hrs/wk @ 4.5 METs = 11.25 MET-hrs/wk

Biosensing





Accelerometry

Principle:

Direct measure of body movement (acceleration)

When a person moves, the body segments are accelerated by muscular forces, which should in theory relate to EE.

Acceleration can be measured along one axis (e.g., longitudinal or vertical), two (e.g., longitudinal + medio-lateral) or three (longitudinal + medio-lateral + anterior-posterior) axes and it can be measured at one or more body sites.



Principles of accelerometry

The measured value of a raw acceleration signal contains **3 components**

1. Acceleration as a result of **movement**
 - The component we are most interested in when estimating activity energy expenditure
2. Acceleration as a result of **gravitational** force
 - In static situations this tells us the orientation of the accelerometer
3. **Noise**

History of accelerometry

Journal of Biomechanics, 1961:

A three-directional accelerometer for analyzing body movements

G. CAYAGU, F. BARBISI AND B. MARGARIA,
Istituto di Fisiologia, Università di Milano, Milano, Italy

One of the most important elements for a comprehensive description of any physiological phenomenon in which movement is involved is the quantitative knowledge of the force which is applied to the body. From the elementary formulation $f = m \cdot a$ it can be seen that this element can be given by the measurement of the acceleration to which the body, or the part of it concerned in the movement, is subjected. Obviously, to obtain the amount and the direction of acceleration, three

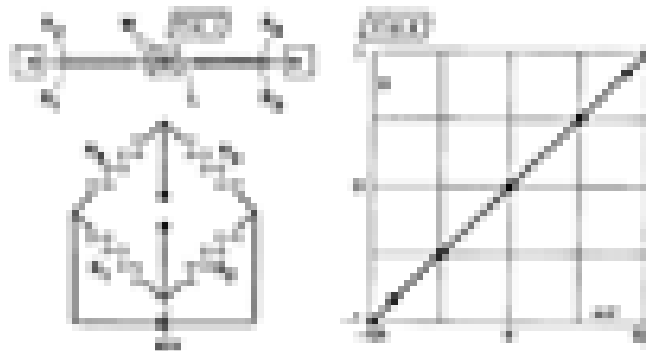


FIG. 1. A, B, C, D = strain gauges, W = weight, d = steel plate.

FIG. 2. Acceleration values in g ($g = 9.81 \text{ m/sec}^2$) are plotted against electrical output (see = substituted) of the accelerometers.

Since three accelerometers oriented perpendicularly to one another must be used,

consider essentially of three steel plates fixed at both extremities, with a weight at the centre, oriented in the three directions of space. On the two surfaces of each plate two resistance strain gauges are applied and the resistance connected in a Wheatstone bridge circuit, as indicated in Figure 1. At zero acceleration there are bending of the steel plates when placed and the strain gauges are balanced so that the output is 0. As an effect of acceleration the plates bend, the strain values change and the Wheatstone bridge is unbalanced. The value of the weight on the plates may be selected or adjusted so as to reach the sensitivity required. The plate displacements are maintained in such limits that inertia is negligible and electrical changes of output are linear in the experimental range (Fig. 3).

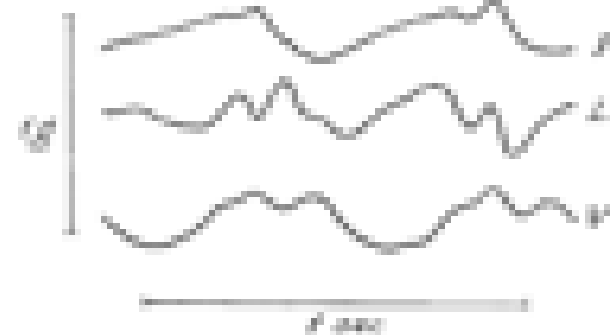
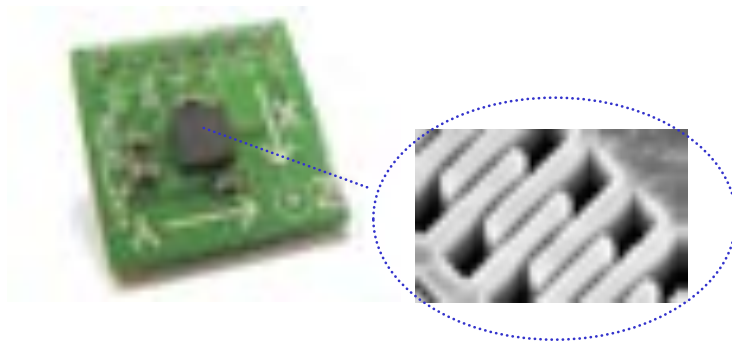


FIG. 3. A is forward, B is lateral, C = vertical component of acceleration during walking.

How does an accelerometer work?



+



Transducer or Sensor

-Energy converter

(e.g., movement to electric signals)

Important characteristics:

Range, sensitivity, linearity, internal frequency, hysteresis, drifts (temperature, humidity, etc)

Data Acquisition System


-Data sampler and pre-processor

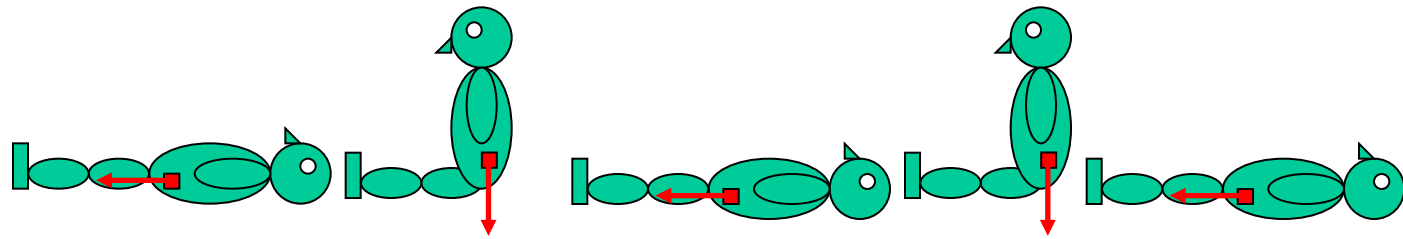
(e.g., raw signals to desirable parameters)

Important characteristics:

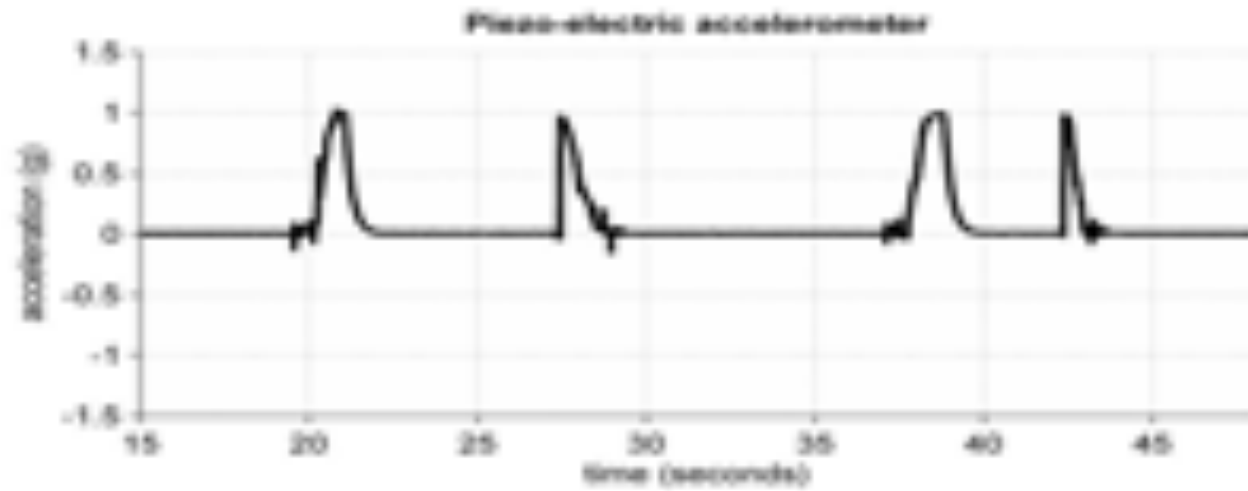
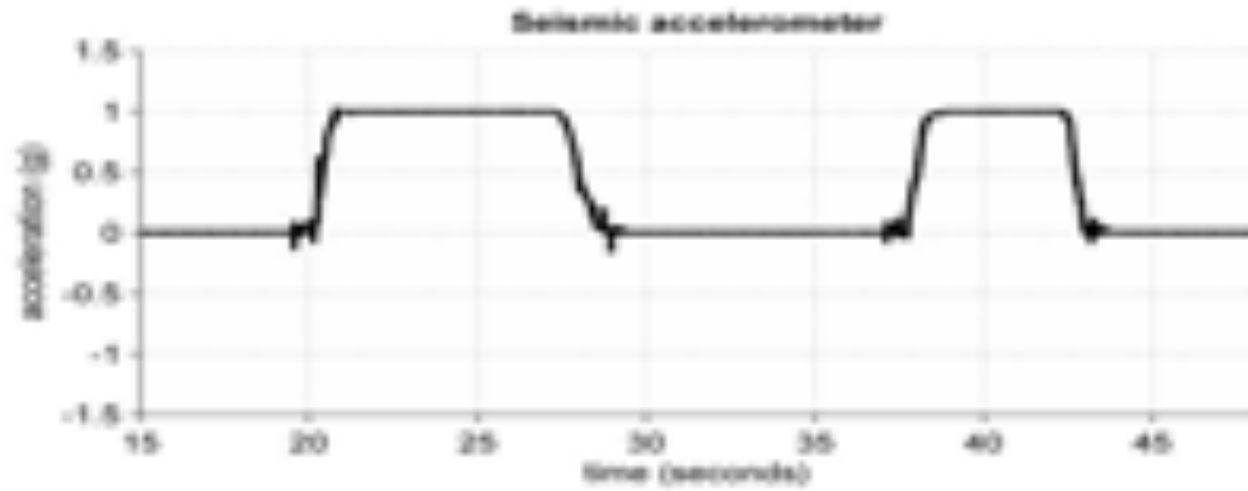
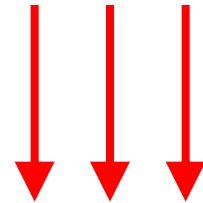
Sampling frequency, signal conditioning, digital signal processing, size, cost

Two types of accelerometers

←  = sensor



gravity



Pop quiz!

A triaxial seismic accelerometer measures the following stable (>3 sec) acceleration values in its 3 axes:

$$X = 0.7g$$

$$Y = 0.7g$$

$$Z = 0.0g$$

What is the orientation of the accelerometer?

*Hint: Vector magnitude = $\sqrt{X^2 + Y^2 + Z^2} = 1$ (when static)
... and you may find your trigonometric math useful too!*

OR open a picture on your smartphone and note when it flips it to landscape viewing! Do the same when shaking it!

Accelerometer auto-calibration to local gravity

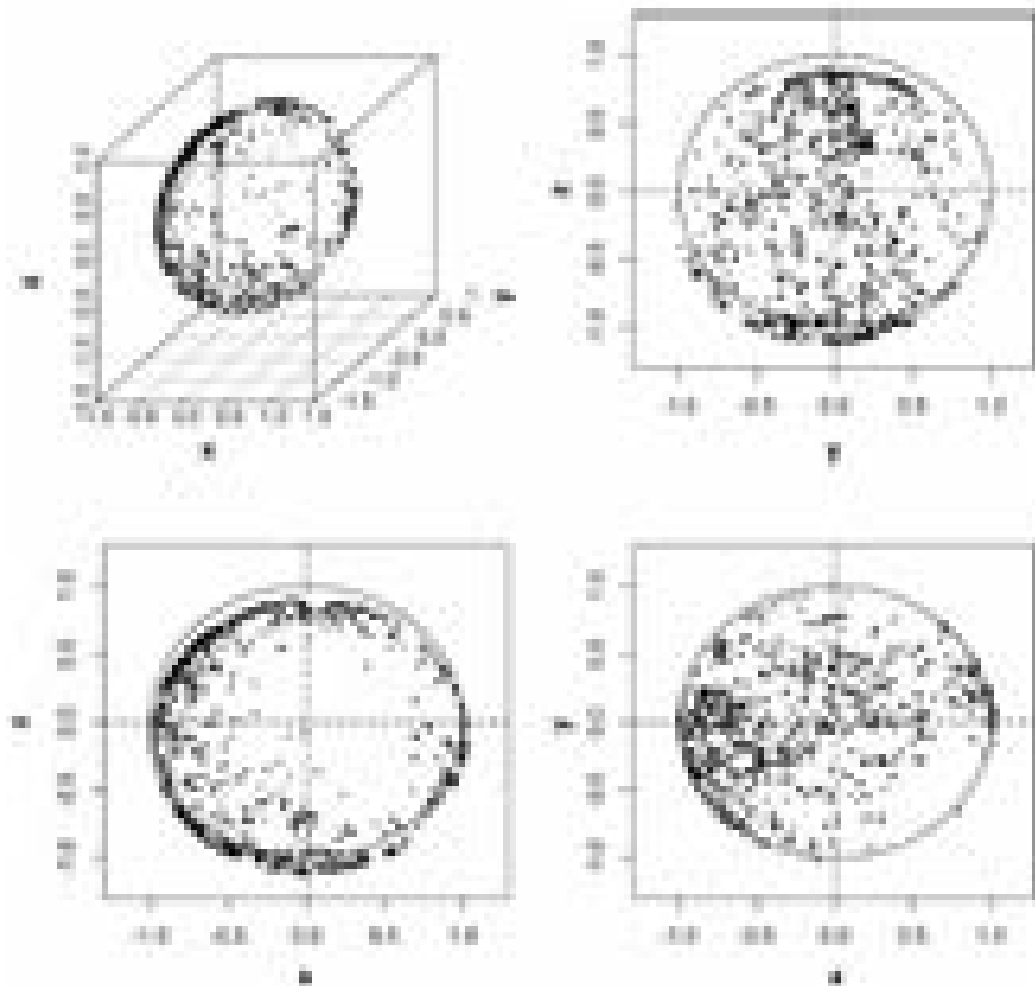
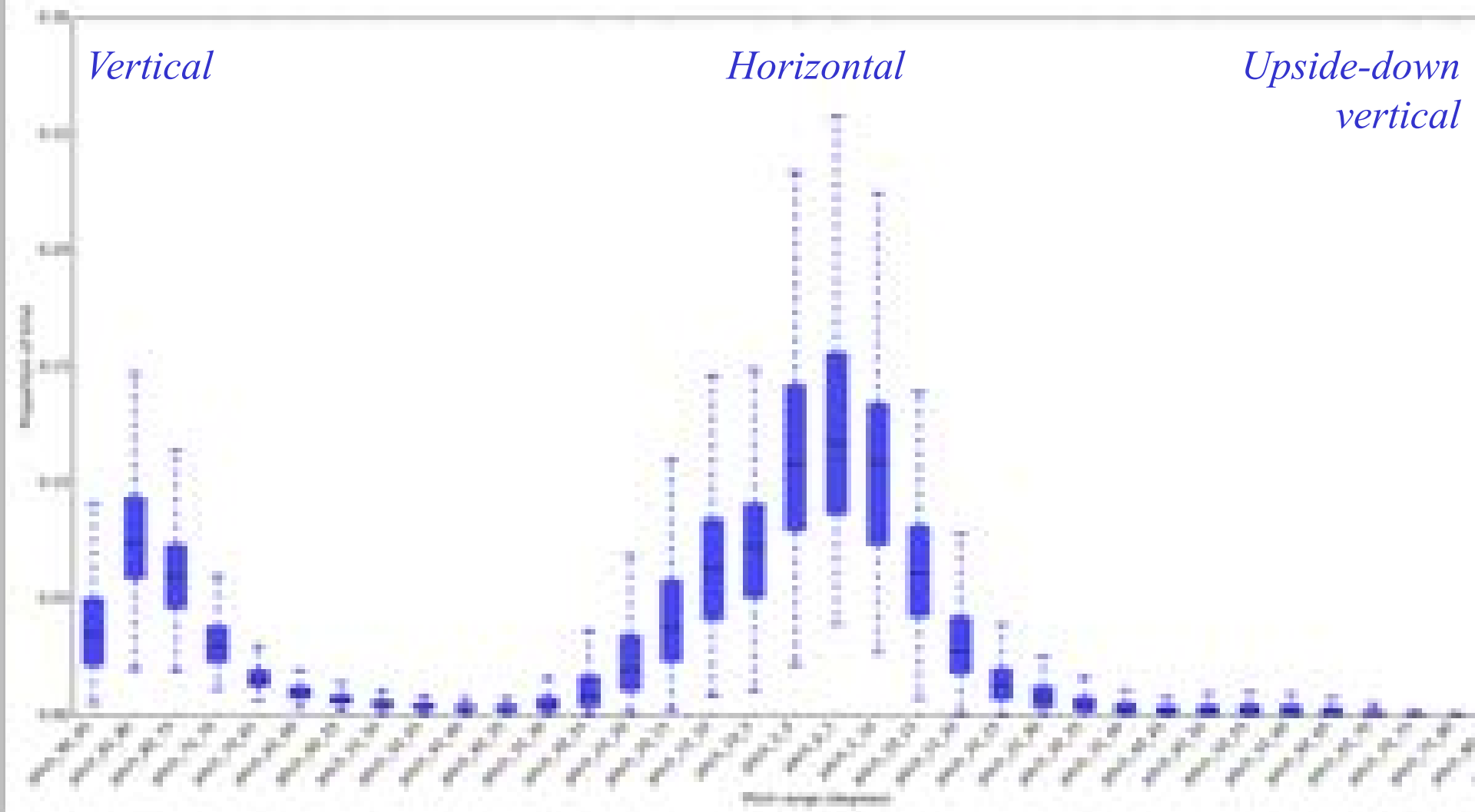


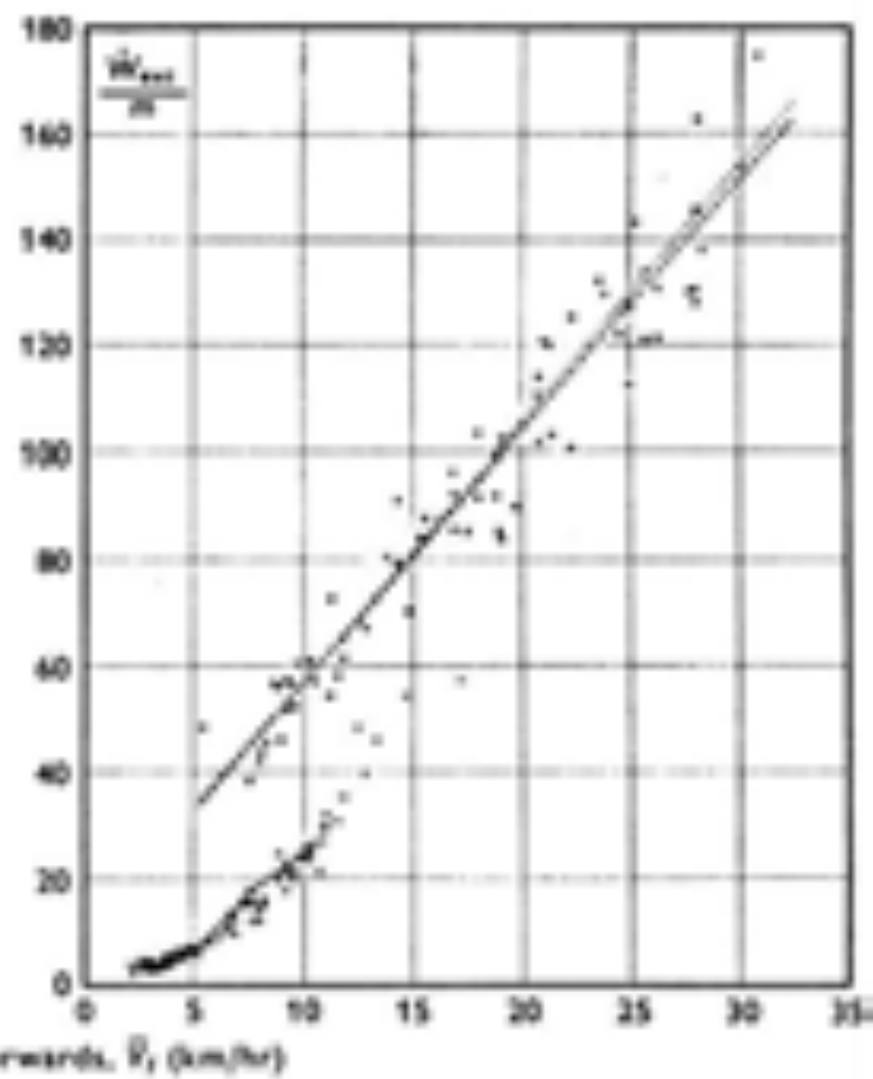
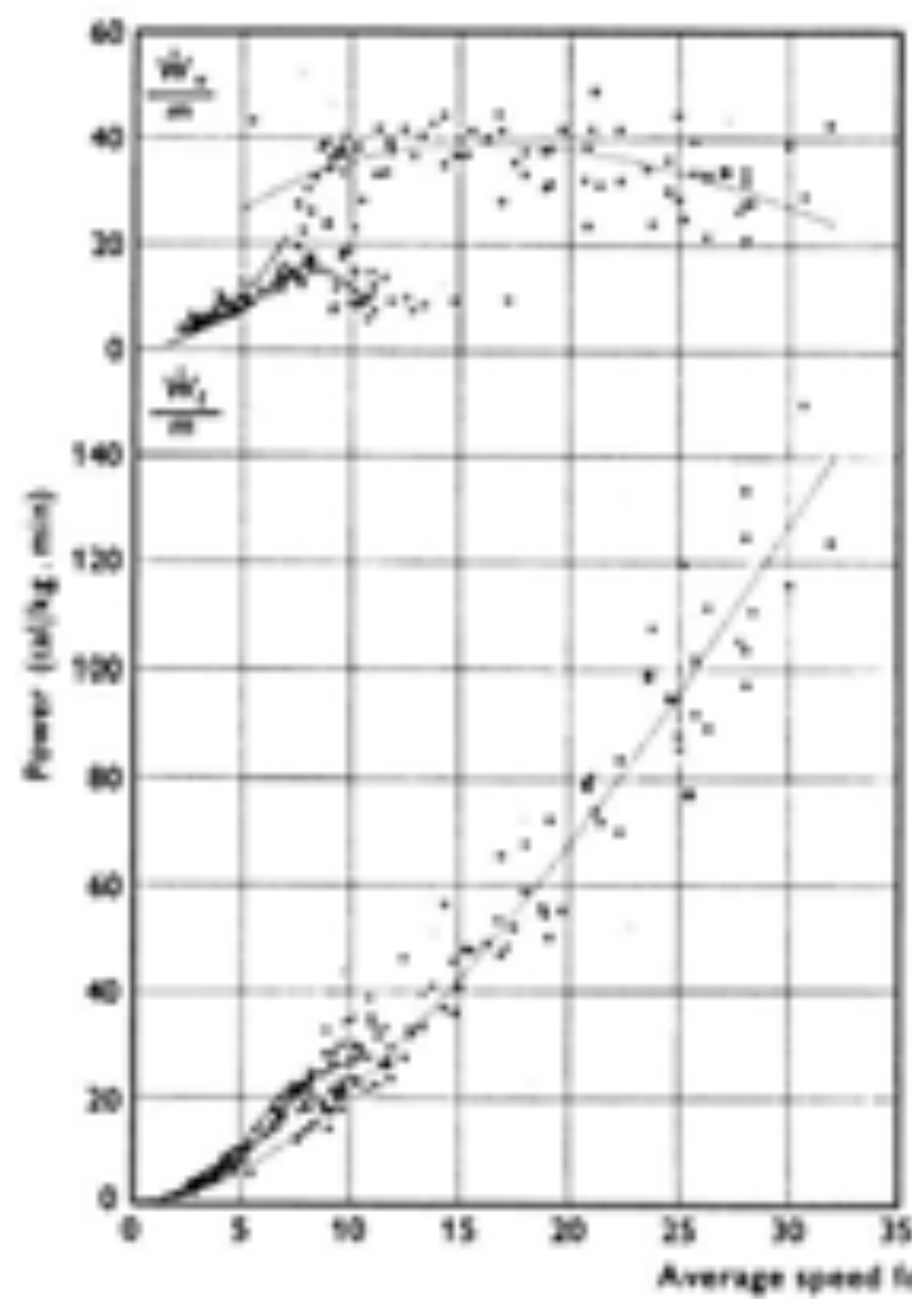
Table 4. Impact of auto-calibration on daily wrist acceleration calculated with metric *ANMO*

Classification	μ_1	μ_2	μ_3
Day			
average	16.4 (16.4)	16.8 (16.8)	16.5 (16.5)
SD	6.2 (6.4)	6.5 (6.5)	6.4 (6.4)
10-90 percentile	1.07 (1.08)	1.04 (1.05)	1.17 (1.15)
25-75 percentile	27.3 (27.1)	26.47 (26)	27.7 (27.4)
90-95 percentile	46.4 (46.4)	46.7 (47.2)	46.4 (47.2)
95-99 percentile	87.4 (87.4)	86.7 (87.4)	86.7 (87.4)
99-100 percentile	113.9 (109)	112.7 (109)	110 (109)
Evening			
average	26.4 (26.1)	26.4 (26.3)	26.5 (26.3)
SD	11.7 (11.2)	11.8 (11.8)	11.7 (10.9)
10-90 percentile	12 (10.2)	11.7 (12.4)	11.1 (10.4)
25-75 percentile	27.4 (27.4)	27.3 (26.2)	27.3 (26.3)
90-95 percentile	56.4 (57.3)	57.2 (58.4)	57.2 (58.4)
95-99 percentile	76.4 (76)	75.2 (75.8)	75.1 (75.4)
99-100 percentile	100.9 (104.4)	99 (104.5)	98.9 (104.4)
Night			
average	11.3 (11.4)	14.7 (13.8)	14.5 (13.4)
SD	10.2 (10.3)	11.4 (10.8)	11.3 (10.9)
10-90 percentile	21.8 (11.1)	16.4 (13.4)	11.4 (10.7)
25-75 percentile	40.4 (23.4)	29.3 (27.3)	26.3 (27.4)
90-95 percentile	60.4 (29.4)	46.4 (28.4)	46.4 (28.4)
95-99 percentile	112.4 (71.4)	96.4 (72.4)	94 (72.3)
99-100 percentile	180.7 (109.1)	176.7 (109.4)	176.7 (109.4)
Weekend			
average	16.4 (17.3)	16.7 (16.7)	16.5 (17.4)
SD	13.4 (15.3)	14.4 (15.3)	13.7 (14.4)
10-90 percentile	10.3 (10.4)	10.4 (10.4)	10.4 (10.3)
25-75 percentile	26.2 (26.7)	26 (26.7)	26.4 (27.4)
90-95 percentile	46.4 (27.3)	46.7 (27.4)	46.7 (27.4)
95-99 percentile	100.4 (77.3)	101.1 (77.3)	101.1 (77.4)
99-100 percentile	183.4 (126)	187.7 (126.3)	186.7 (126.3)

Thigh acceleration:

Pitch angle distribution during static periods of free-living

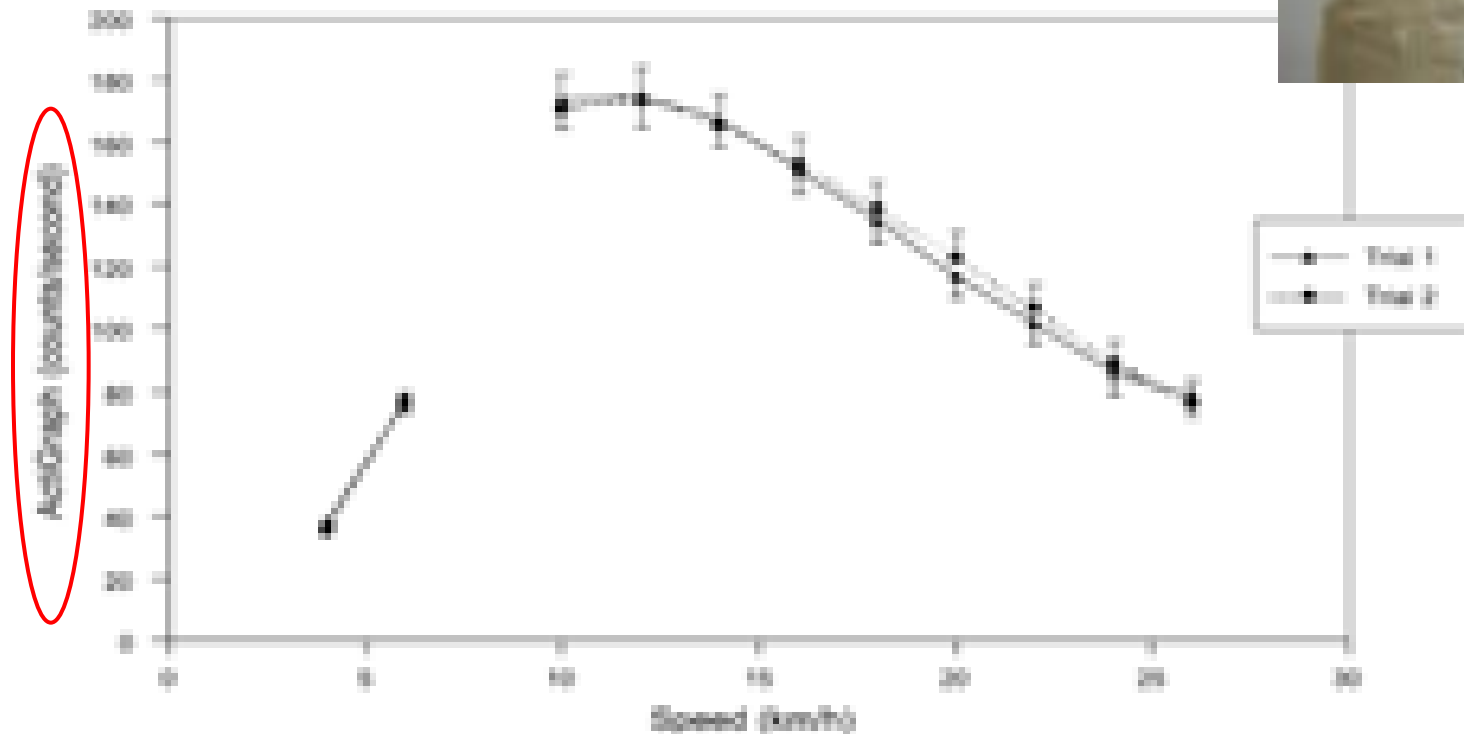




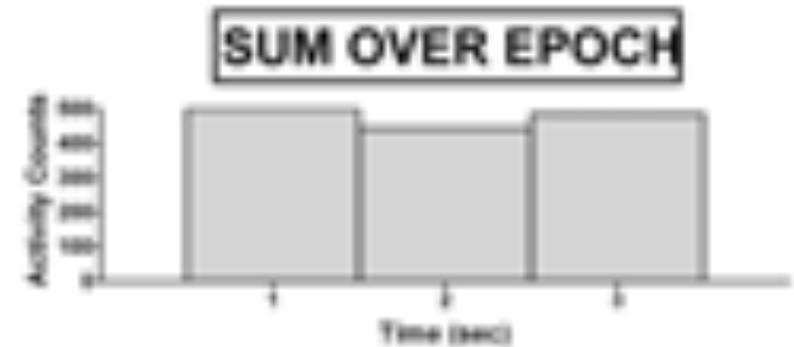
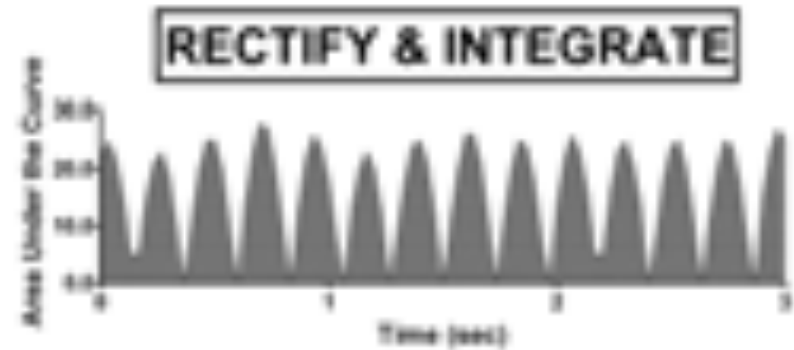
Influence of Speed and Step Frequency during Walking and Running on Motion Sensor Output

ANN V. ROWLANDS, MICHELLE R. STONE, and ROGER G. EATON

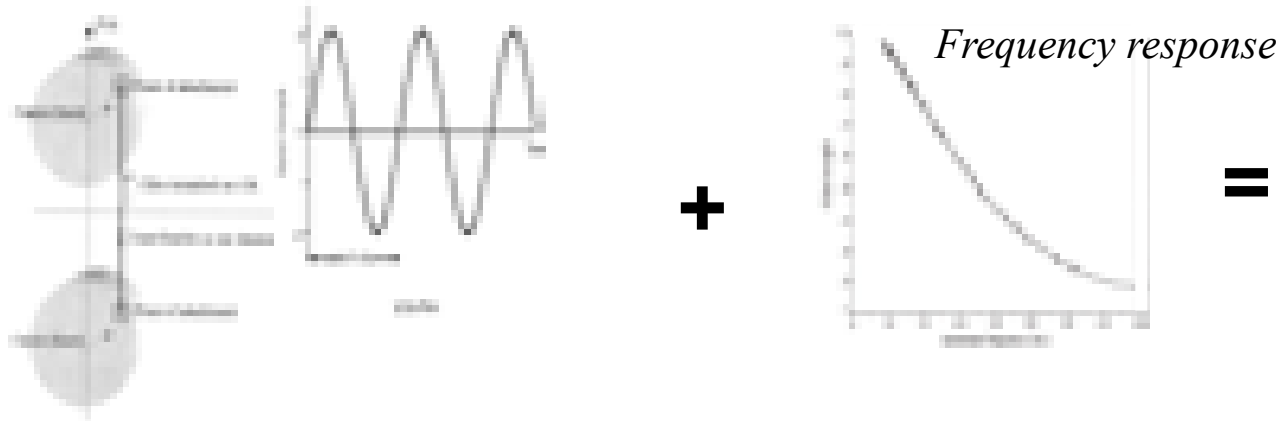
School of Sport and Health Sciences, University of Exeter, UNITED KINGDOM



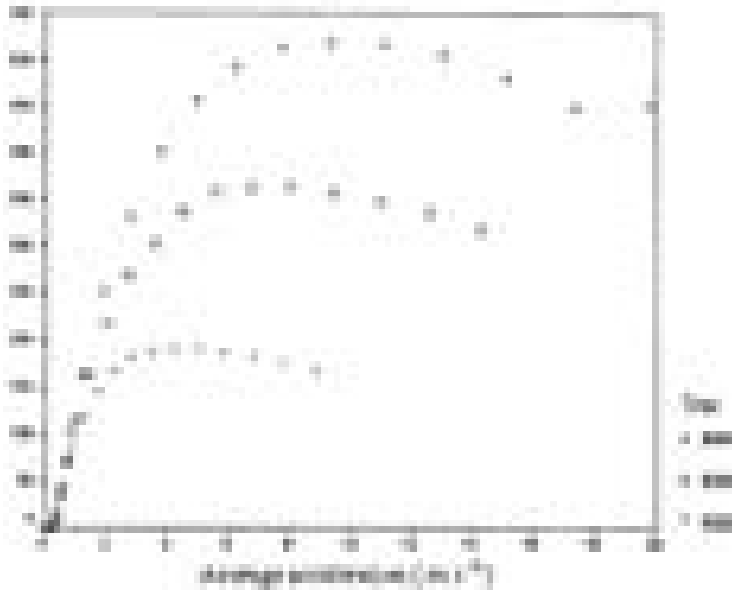
Data processing



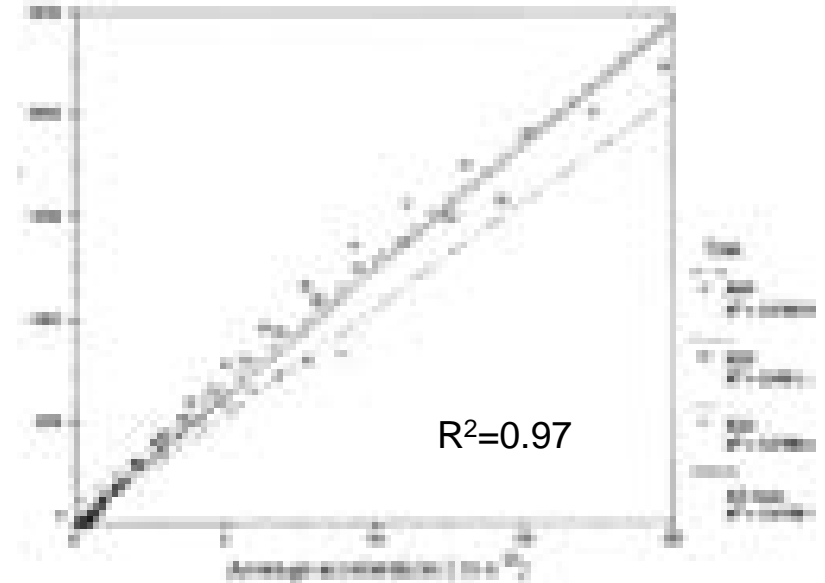
Actigraph acceleration response

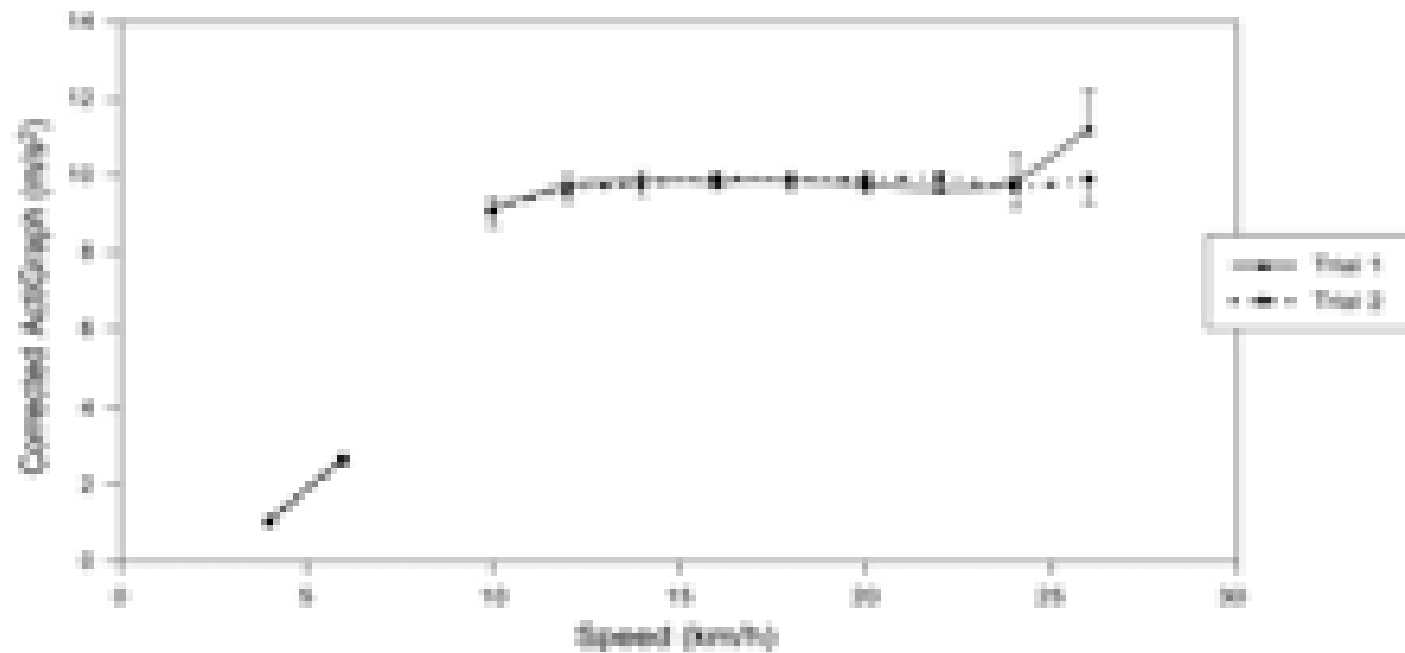
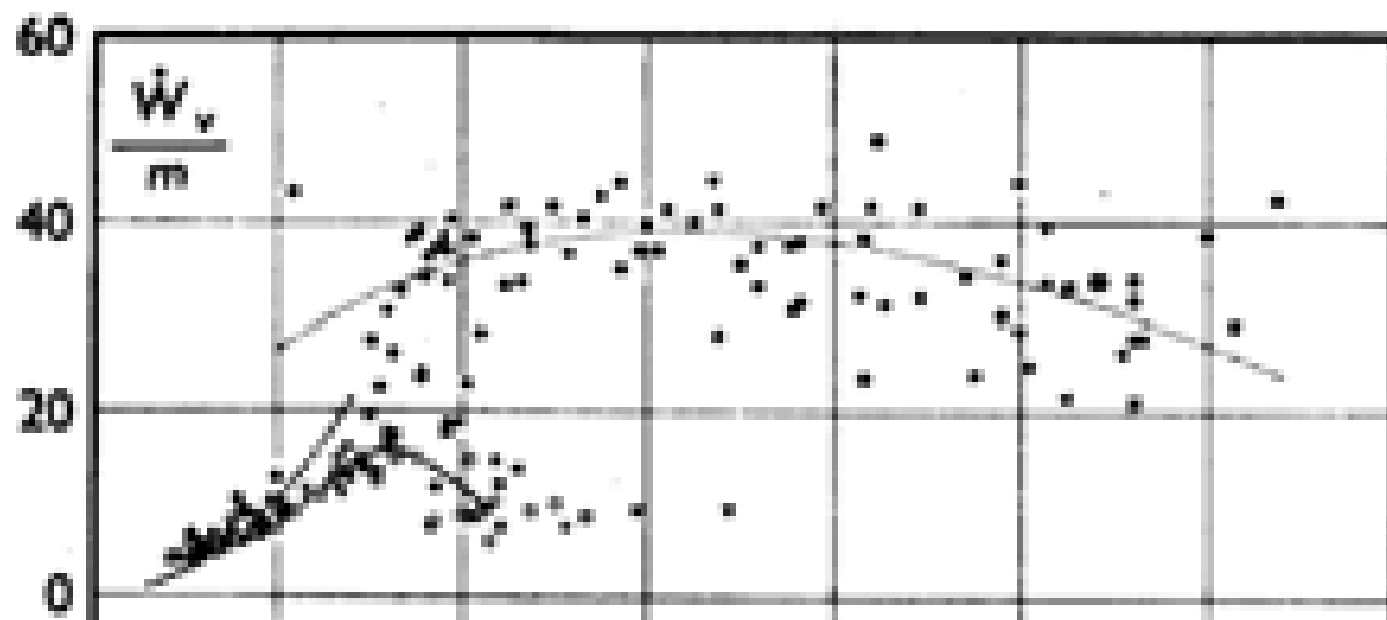


Actigraph counts vs $1/T \int |\text{acceleration}| dt$

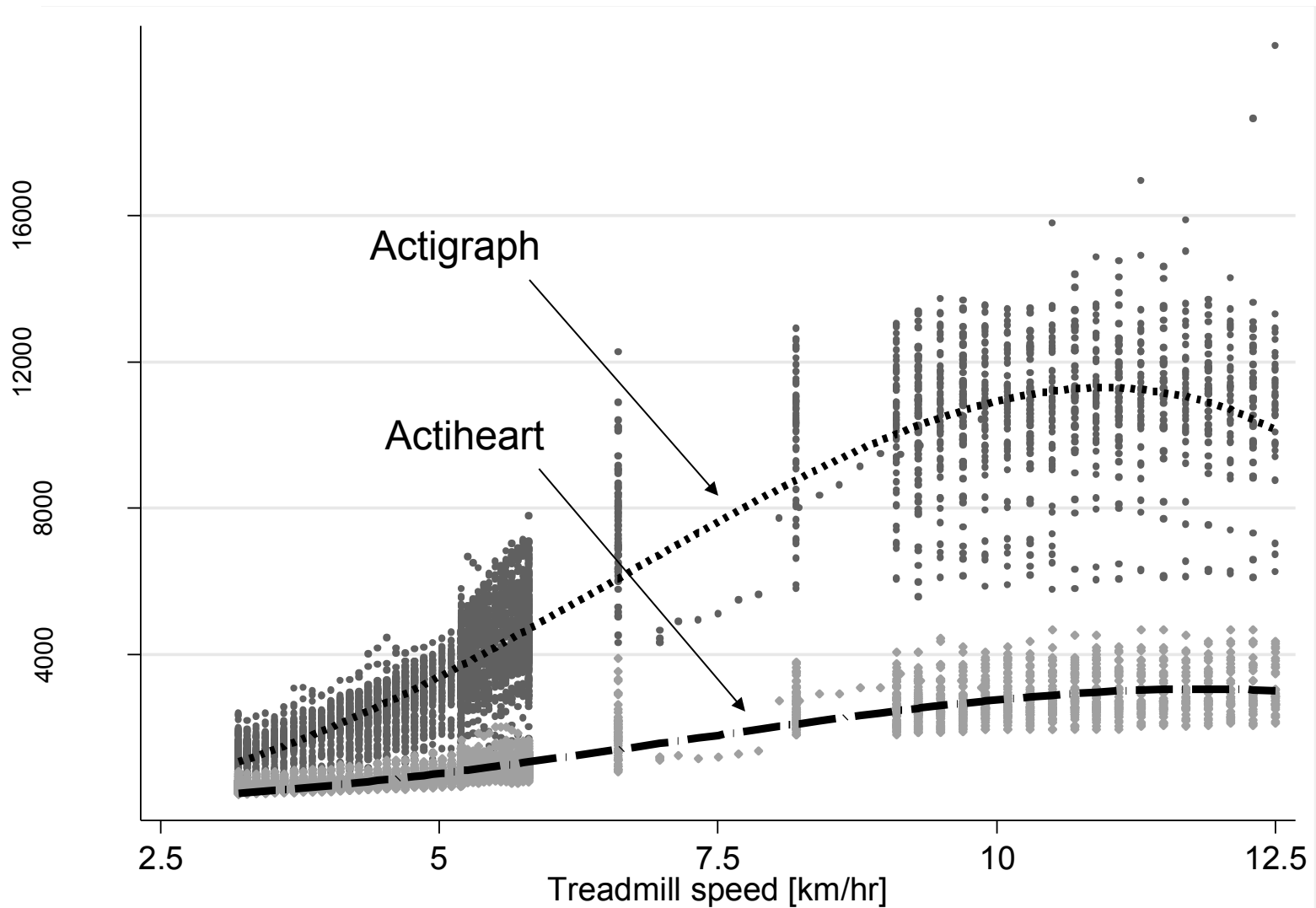


Filter-corrected counts

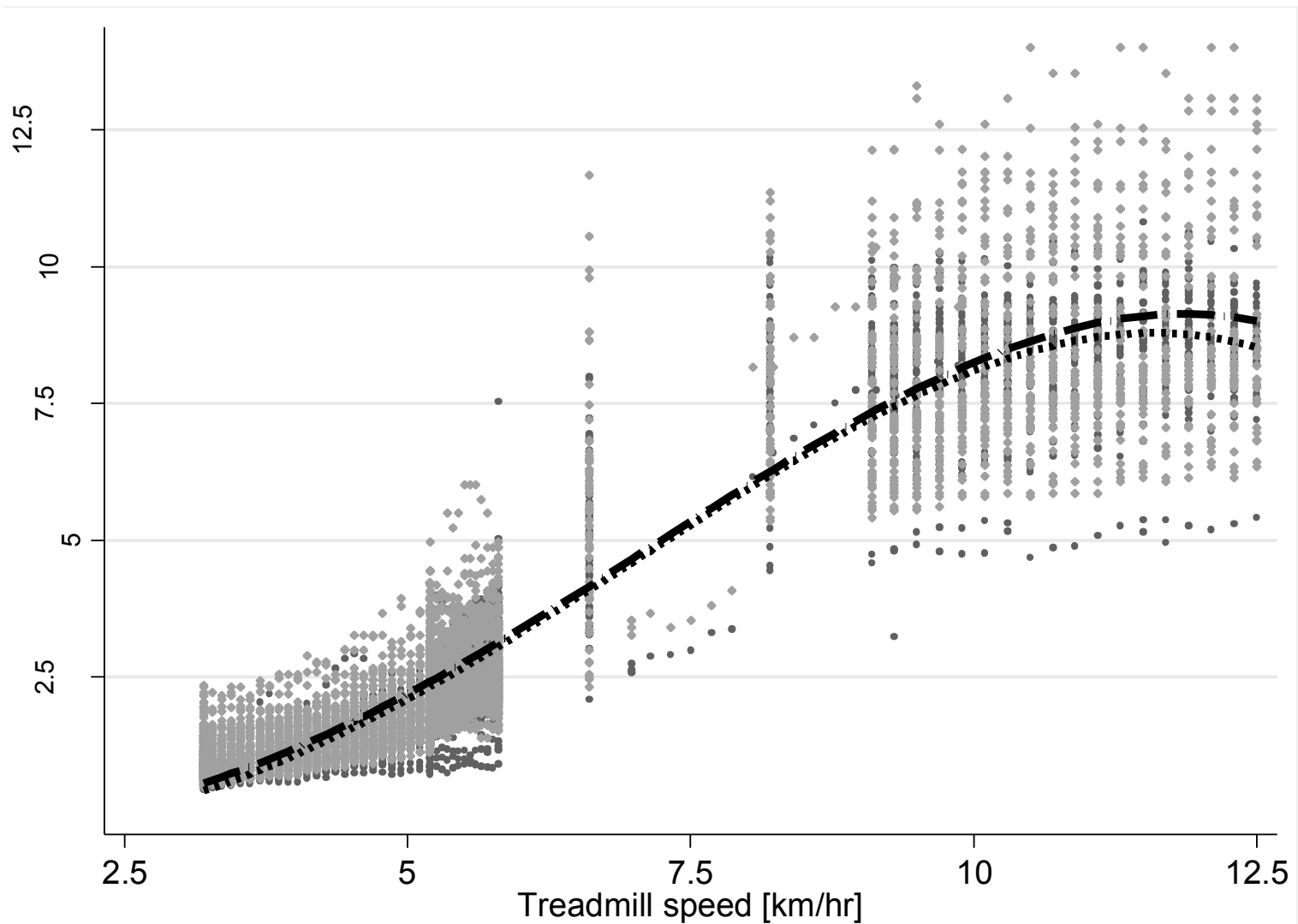




Accelerometry output in “counts per min”



Accelerometry output expressed in m/s^2

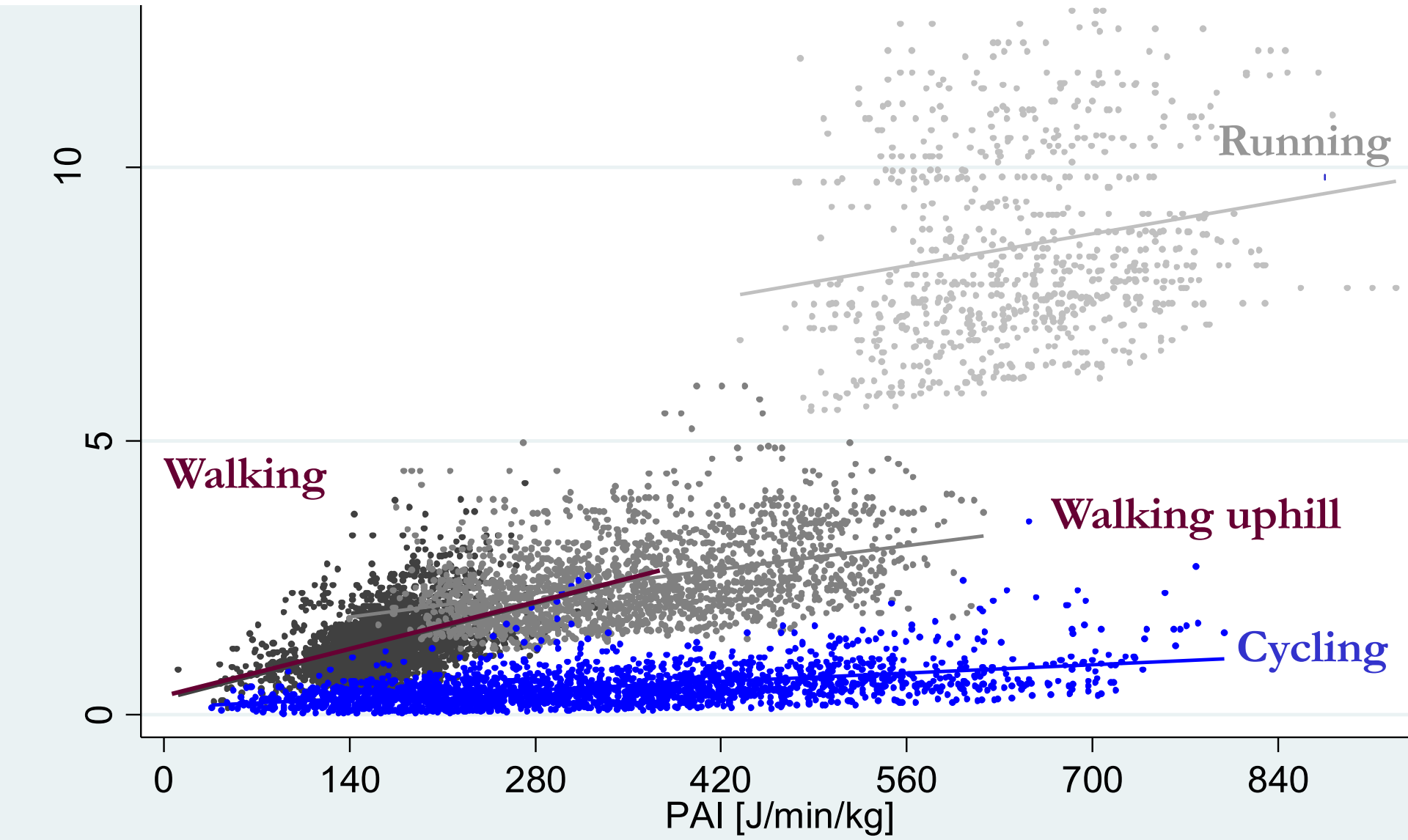


Modeling energy expenditure

(making bolder inferences!)

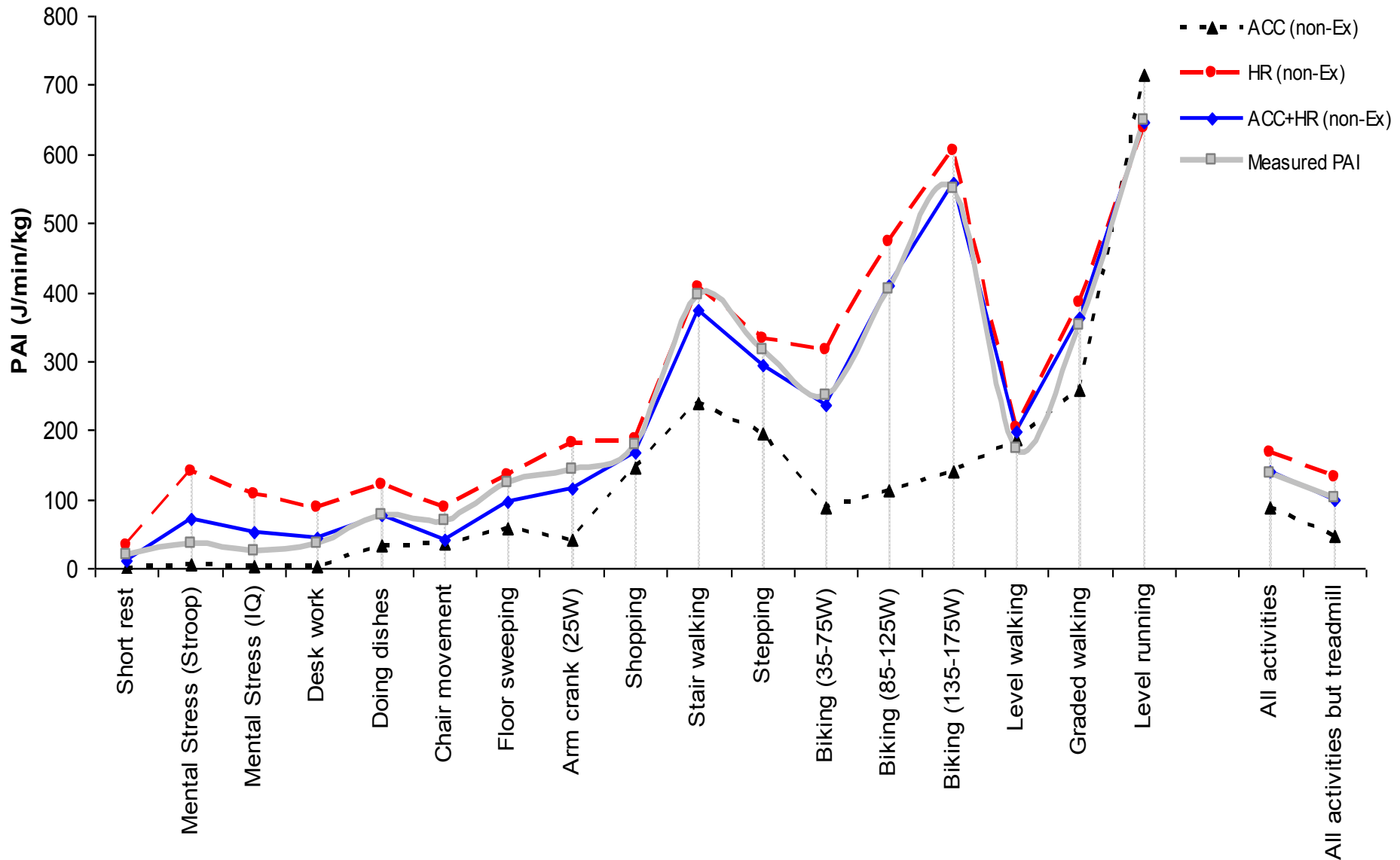
Accelerometry (magnitude):

Variability in the Acc-PAI relationship by mode of activity



ACC (BLACK), HR, and ACC+HR during different activities

PAI reference: breath² VO₂+VCO₂ (GREY)



AEE estimated by waist-worn triaxial accelerometer

Estimating Energy Expenditure from Raw Accelerometry in Three Types of Locomotion

James M. Brackley¹, Christopher E. R. A. Jones², Richard W. Stevenson³ and Robert M. A. Jones⁴

¹ School of Health Sciences, University of Strathclyde, Glasgow, Scotland; ² NHS, Glasgow; ³ Glasgow School of Life Sciences, University of Strathclyde, Glasgow, Scotland; ⁴ School of Health Sciences, University of Strathclyde, Glasgow, Scotland

“Acceleration was summarised by applying a 4th order Butterworth filter (ω_0 0.1 – 15 Hz) to each axis...”

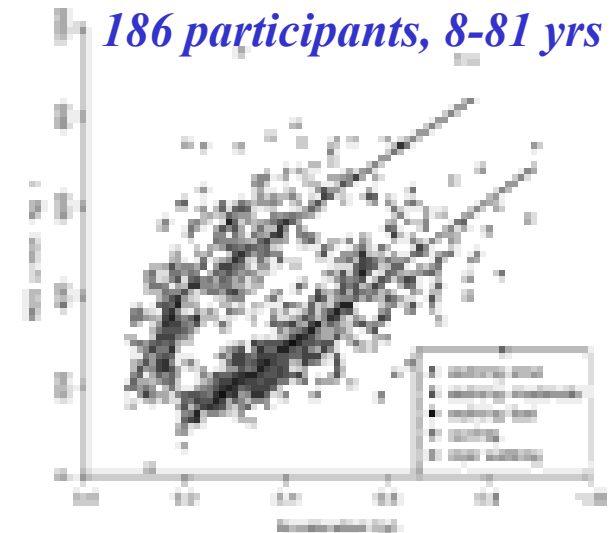


TABLE 1. Summary of results for predicting AEE during walking, walking + sitting, and total walking.

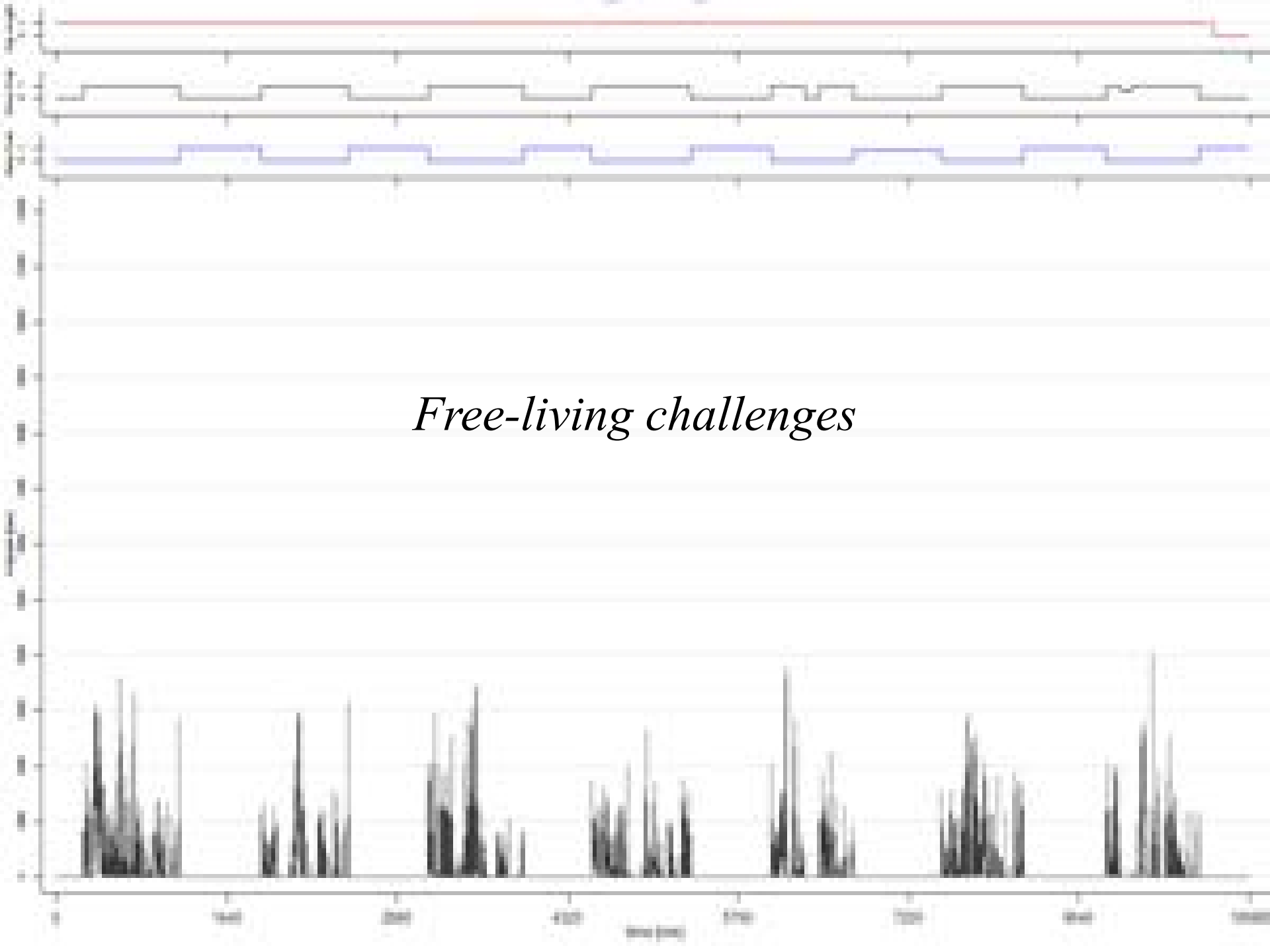
Dependent	Independent	Walking ¹		Walking ²		Total Walking ³	
		r ²	RMSE	r ²	RMSE	r ²	RMSE
AEE (kcal/min) ⁴	Height ⁵	0.188	0.17	0.188	0.18	0.191	0.18
	Height ⁶ + Age ⁶	0.192	0.16	0.197	0.16	0.195	0.16
	Height + Age + weight + Age ⁶	0.194	0.16	0.198	0.16	0.197	0.16
	Height + Age + weight + Age ⁶ + gender ⁷	0.197	0.16	0.197	0.16	0.196	0.16
	Height + Age ⁶ + weight + Age ⁶ + gender + gender × Age	0.197	0.16	0.197	0.16	0.196	0.16
	Height + Age + weight + Age ⁶ + Age	0.198	0.16	0.199	0.16	0.197	0.16
	Height ⁶ + Age + weight + Age ⁶ + Age ⁶ + Age × Age ⁶	0.197	0.16	0.197	0.16	0.196	0.16
	Height ⁶ + Age + weight + Age ⁶ + Age ⁶ + Age × Age ⁶ + Age ⁶	0.197	0.16	0.197	0.16	0.196	0.16
AEE (kcal/min) ⁴ log ⁸	Age ⁶	0.197	0.16	0.197	0.16	0.196	0.16
	Age ⁶ + gender ⁷	0.198	0.16	0.198	0.16	0.197	0.16
	Age ⁶ + gender ⁷ + gender × Age	0.198	0.16	0.198	0.16	0.197	0.16
	Age ⁶ + Age	0.197	0.16	0.197	0.16	0.196	0.16
	Age ⁶ + Age ⁶ + Age × Age ⁶	0.197	0.16	0.197	0.16	0.196	0.16
	Age ⁶ + Age ⁶ + Age × Age ⁶ + Age ⁶	0.197	0.16	0.197	0.16	0.196	0.16

All models were significant at the P < 0.01 level. Significance P < 0.05 indicated for individual terms in models is as follows: a, all types of locomotion (walking, walking + sitting, and total walking); b, walking; c, walking + sitting; d, total walking.

¹ Based on 100 observations (100 Hz and 100 observations of vertical axis and foot speed respectively).

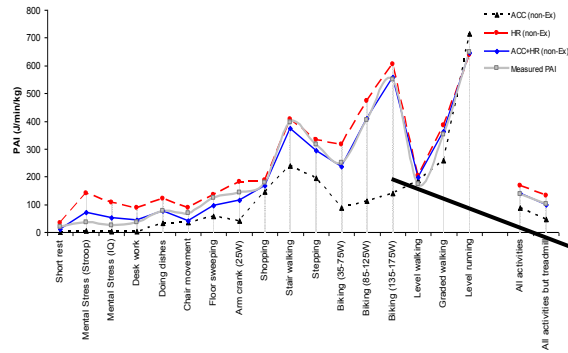
² Based on 170 observations.

³ Based on 170 observations.



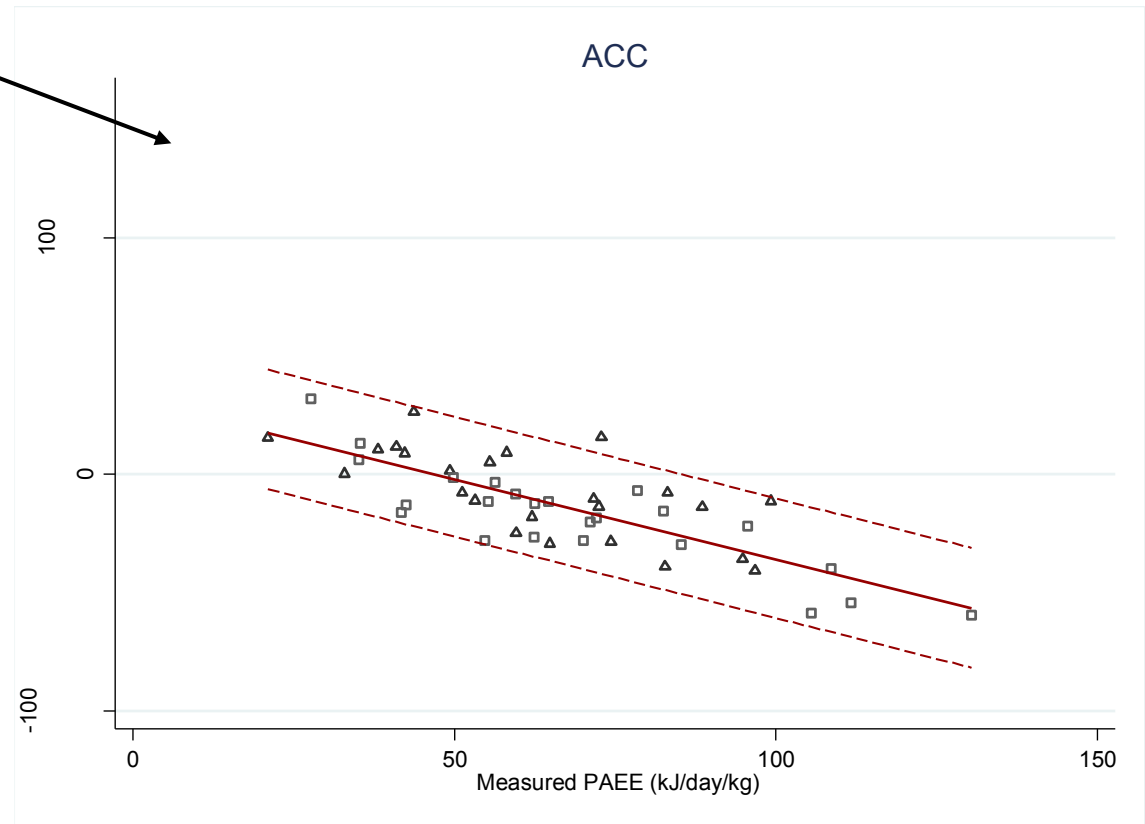
Free-living challenges

Estimation of free-living PAEE from uniaxial magnitude-based chest accelerometry model



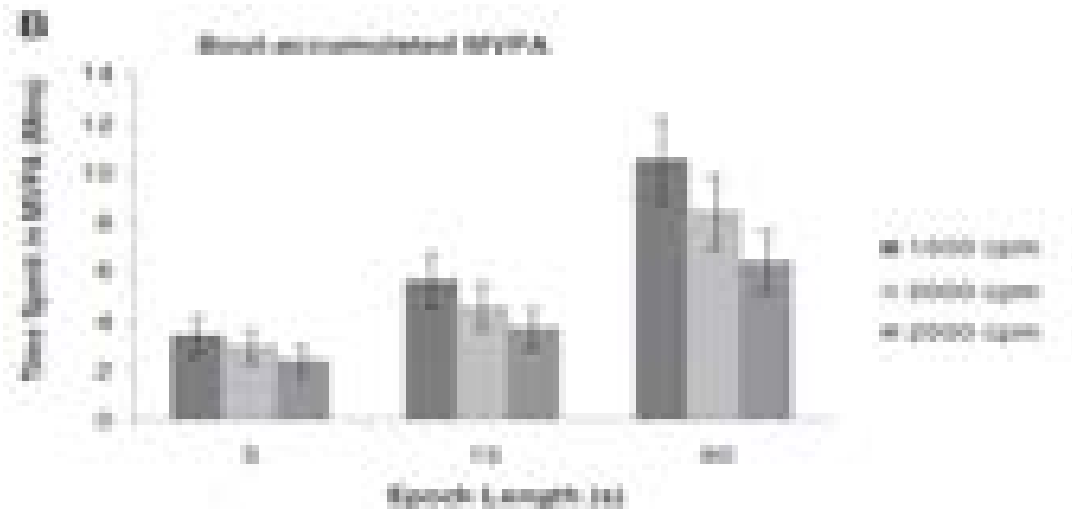
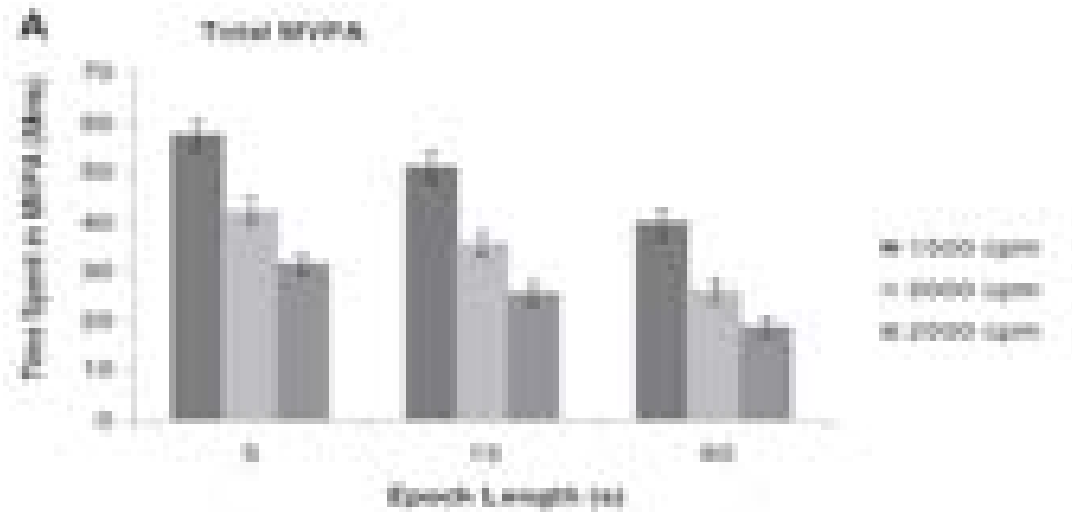
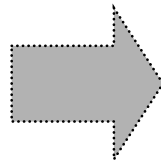
N=46 UK adults, 20-55 yrs

Est. - measured PAEE (kJ/day/kg)



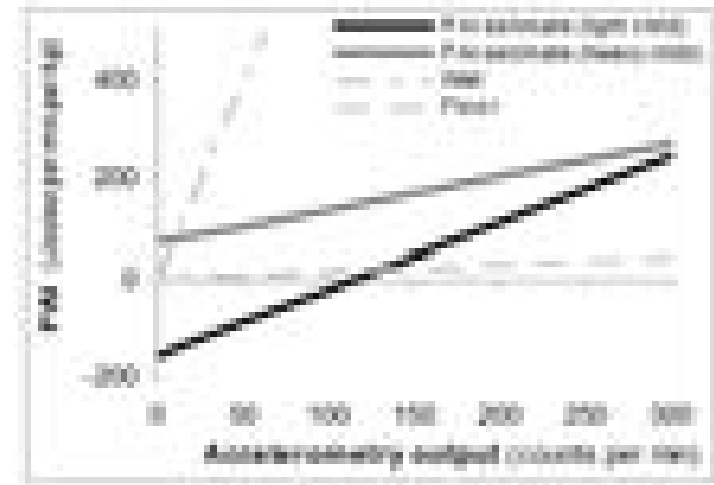
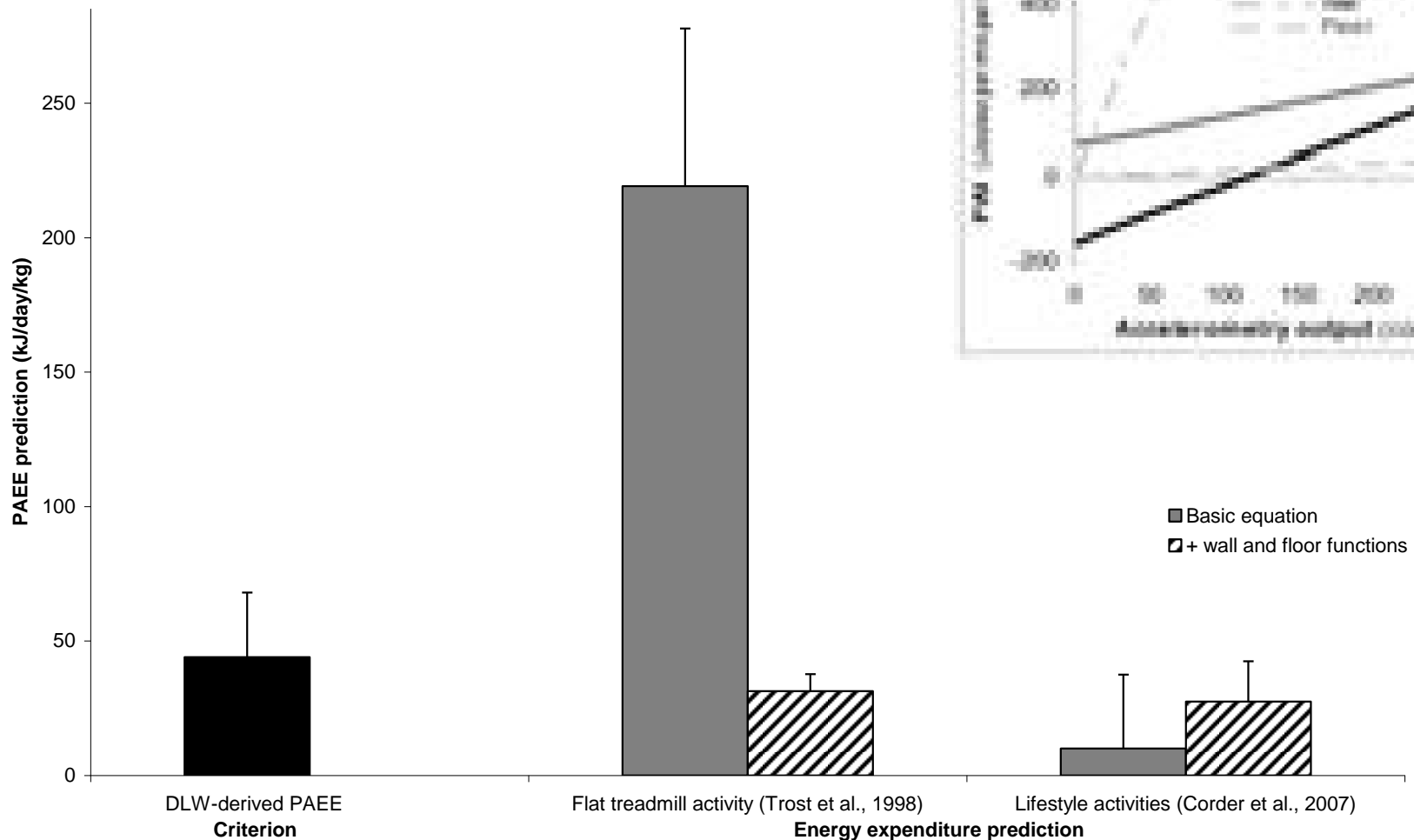
Cutpoints, epochs, bouts ...

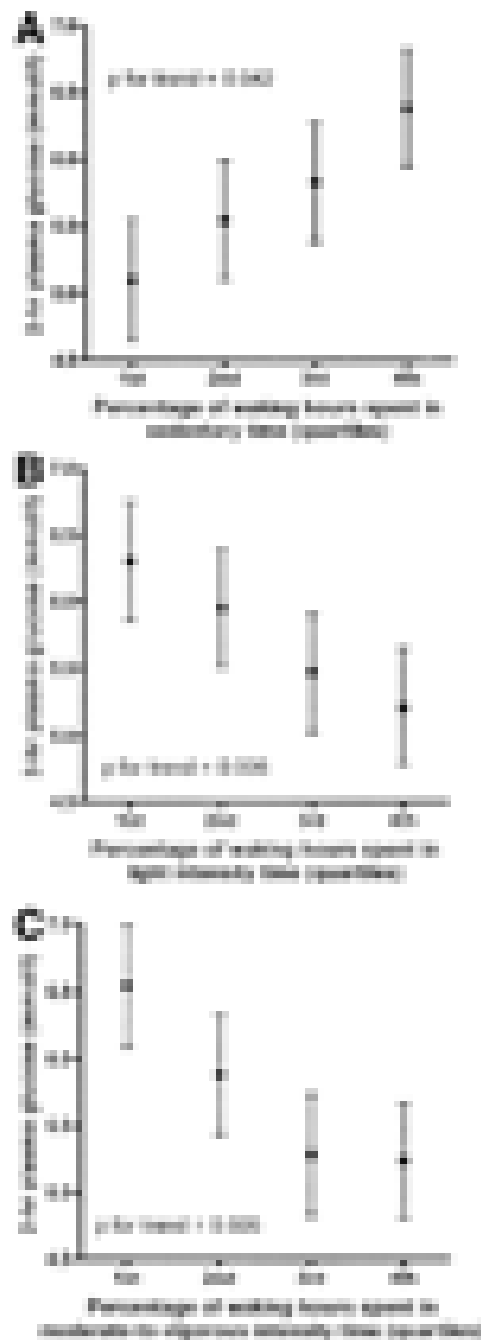
Same raw data



Modifying published prediction equations for activity intensity

Effect of censoring implausible estimates





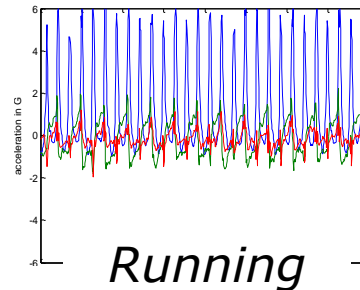
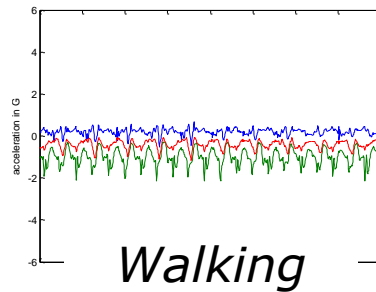
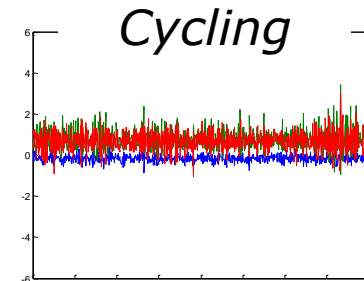
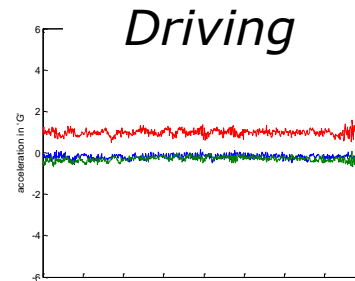
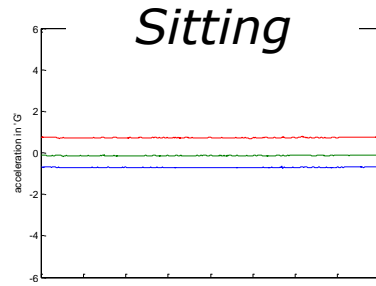
AusDiab:

Objectively (accelerometer) measured **sedentary** behaviour, **light-intensity** physical activity, and **moderate intensity** associated with 2-hr plasma glucose.

Source: Healy et al. Diabetes Care 2007



Waveform accelerometry in large cohorts



N~100,000

Validity

Vector magnitude \sim AEE_{DLW} : $r=0.61$

Vector magnitude \sim AEE_{Acc+Hr}: $r=0.66$

Van Hees et al 2013, 2014; White et al 2017; Doherty et al 2017

General activity classification:

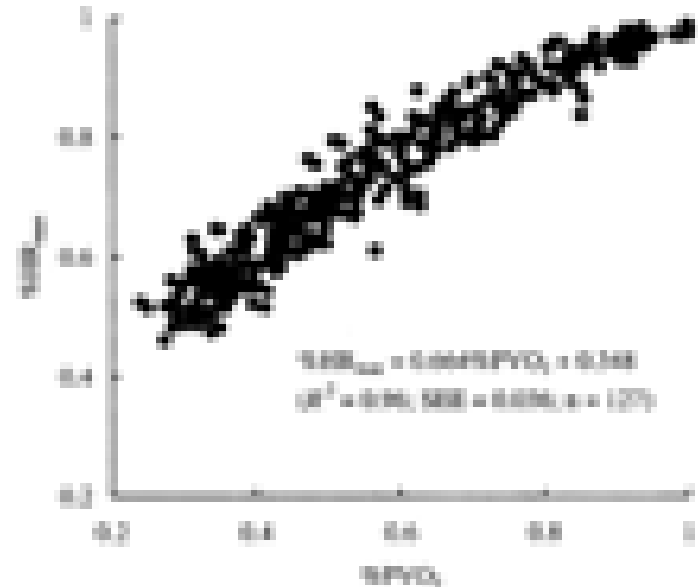
Machine-learning using camera criterion

- **Photo every 20 sec**, then manually (researcher) coded activity type
- **126 signal features** -> **Random Forest** (collection of decision trees) classifier

Table 1. Percentage of machine-learned behaviours automatically classified from wrist-worn accelerometer data. Confusion matrix after leave-one-out validation on 84,818 labelled minutes of human activity in free-living environments: the CAPTURE-24 study 2014-2015 ($n = 57$).

Prediction— Ground truth	Sleep	Sit/stand	Vehicle	Walking	Mixed- activity	Bicycling
Sleep	85%	4%	<1%	<1%	1%	<1%
Sit/stand	4%	85%	1%	2%	6%	0%
Vehicle	<1%	8%	81%	4%	7%	0%
Walking	<1%	13%	1%	51%	33%	2%
Mixed-activity	<1%	11%	3%	11%	75%	1%
Bicycling	<1%	<1%	3%	15%	7%	75%

Heart Rate Monitoring



(Eur J Appl Physiol, 2001)

Principle:

There is a linear relationship between heart rate and energy expenditure during steady state work loads with large muscle groups (e.g., walking, cycling, running)

Minute-by-Minute Heart Rate Monitoring

- HR is a physiological response and therefore an indirect measure of physical activity
- HR may be affected by other factors than PA (e.g. stress, climate, dehydration)

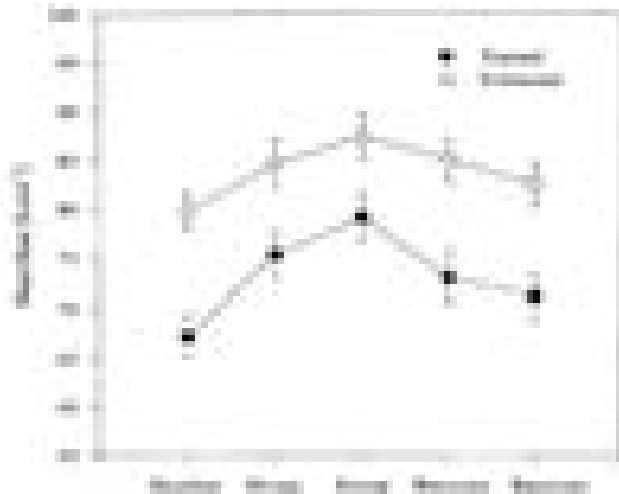
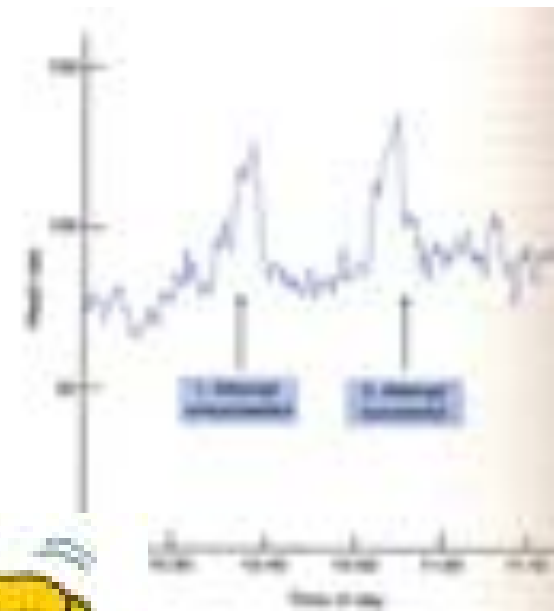


FIGURE 14-100. Maximum heart rate, maximum oxygen uptake, and maximum power output during the sprint and submaximal activities shown in Figure 14-99.

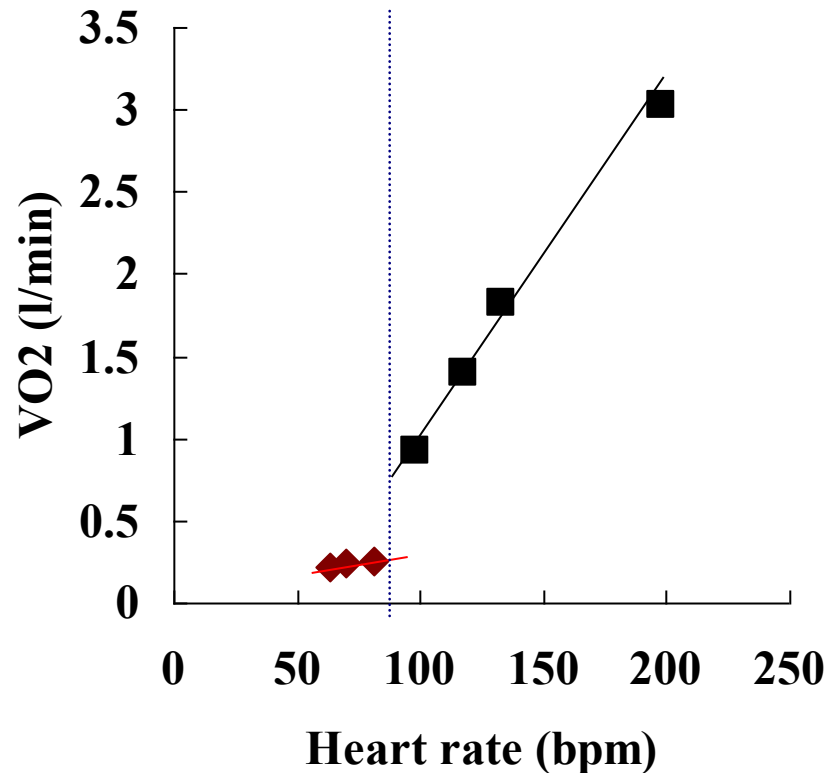


Individual calibration test (CR fitness assessment)



The FLEX HR Method

(Spurr *et al.* 1988)



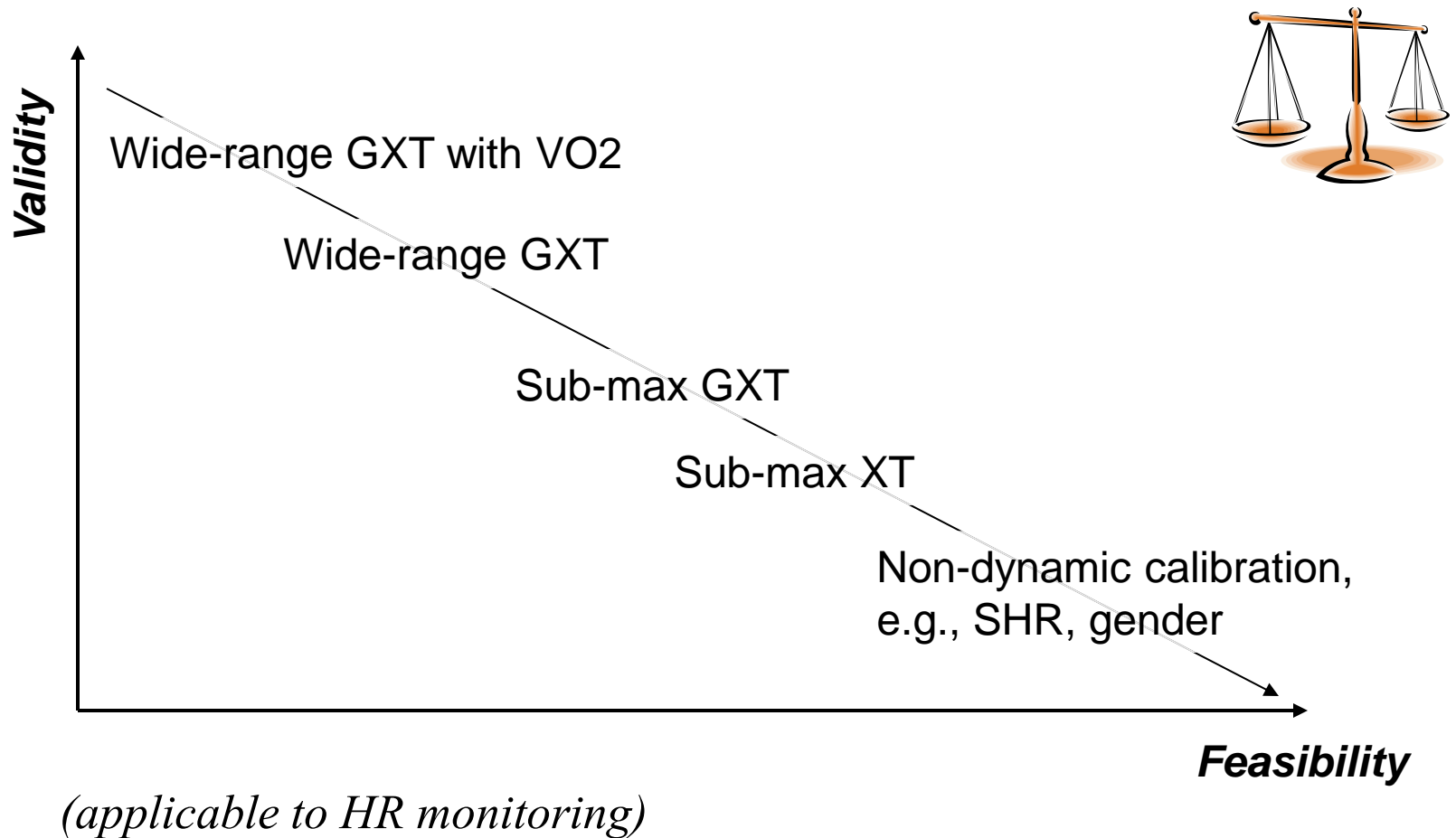
- **CALIBRATION TEST:** Assessment of energy expenditure and HR (supine rest, sitting, standing, exercising)
- **DERIVE:** Individually determined FLEX HR and HR-EE relationship
- **MONITOR:** Min-by-min HR during free-living and apply derived calibration factors to estimate intensity (EE)

HR calibration models

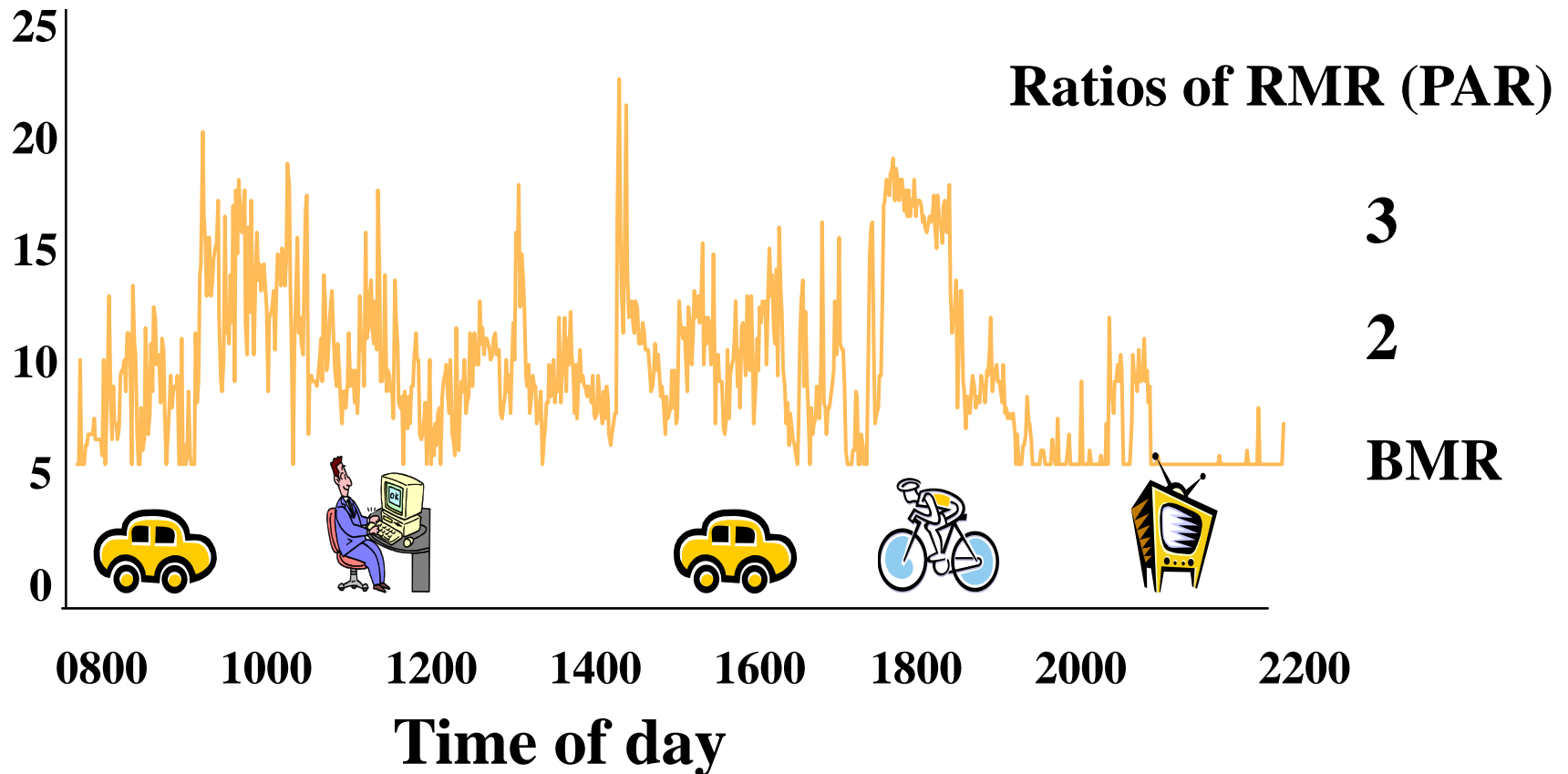
Calibration level		R ²		
		<i>within</i>	<i>between</i>	<i>overall</i>
I.	TM + VO2	.975	.999	.977
II.	TM	.963	.808	.947
III.	Step + VO2	.947	.676	.913
IV.	Step	.948	.675	.919
V.	Walk + VO2	.928	.614	.888
VI.	Walk	.928	.590	.892
VII.	Non-exercise (static)	.924	.302	.812

Individual calibration hierarchy

Balancing validity and feasibility



Energy Expenditure – Flex HR method



$$TEE = EE_{\text{sleep}} + EE_{\text{rest}} + EE_{\text{act}}$$

$$EE_{\text{sleep}} = 0.95 * REE$$

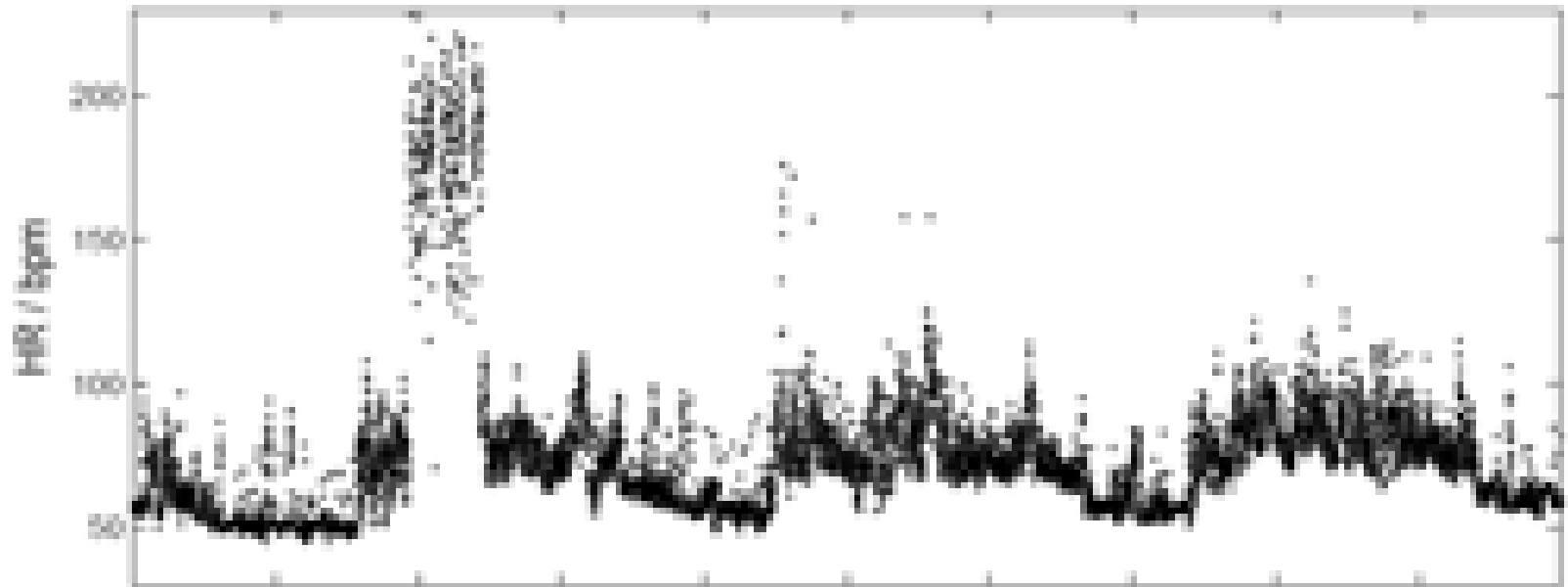
$$EE_{\text{rest}} = REE \text{ (for HR} < \text{FLEX HR)}$$

$$EE_{\text{act}} = EE \text{ from regression equation (for HR} \geq \text{FLEX HR)}$$

Free-living challenges: data are noisy and incomplete!



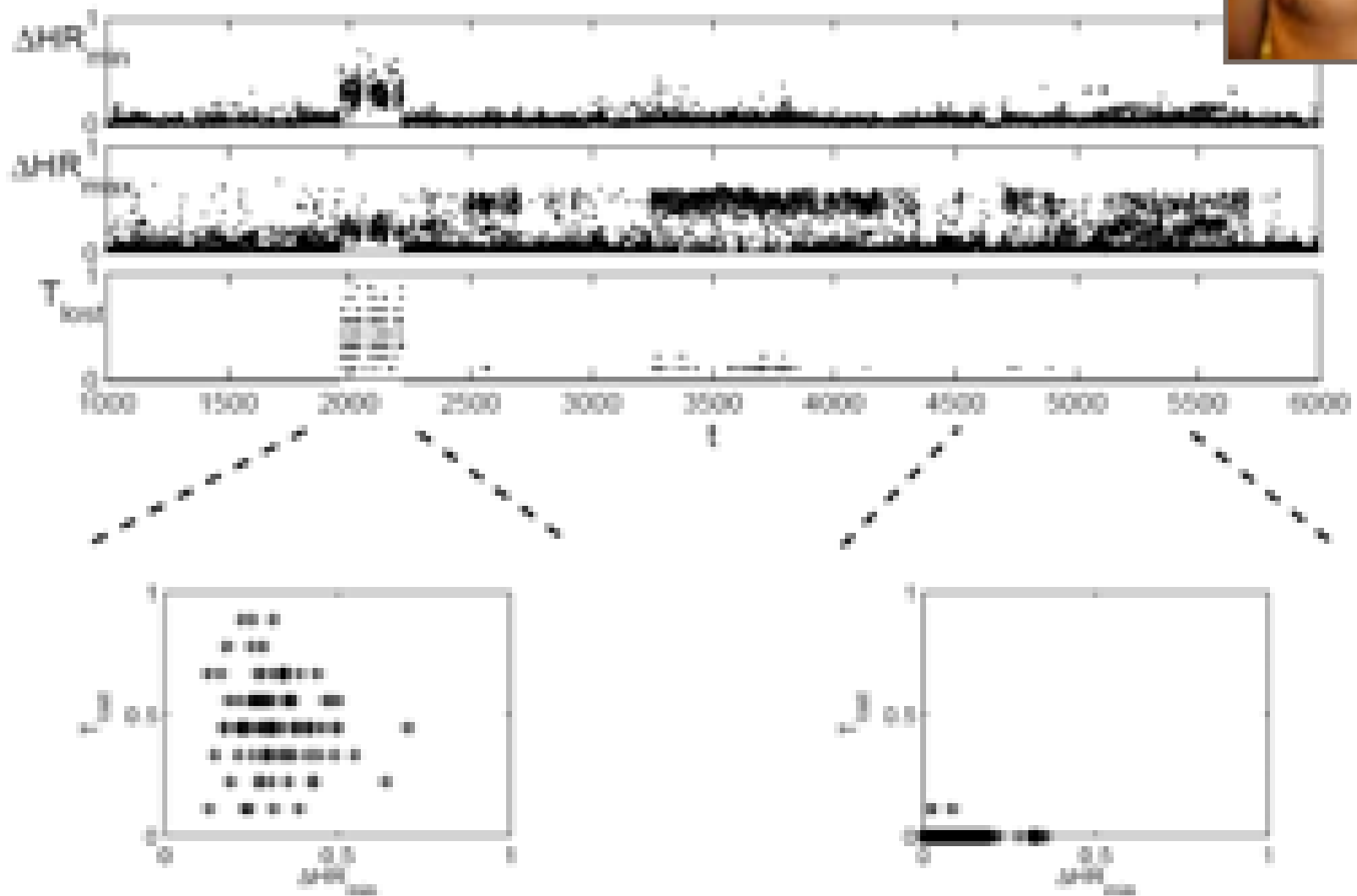
HR measurement noise



Standard average heart rate minute-by-minute

1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000

Noise detection



HR inference model

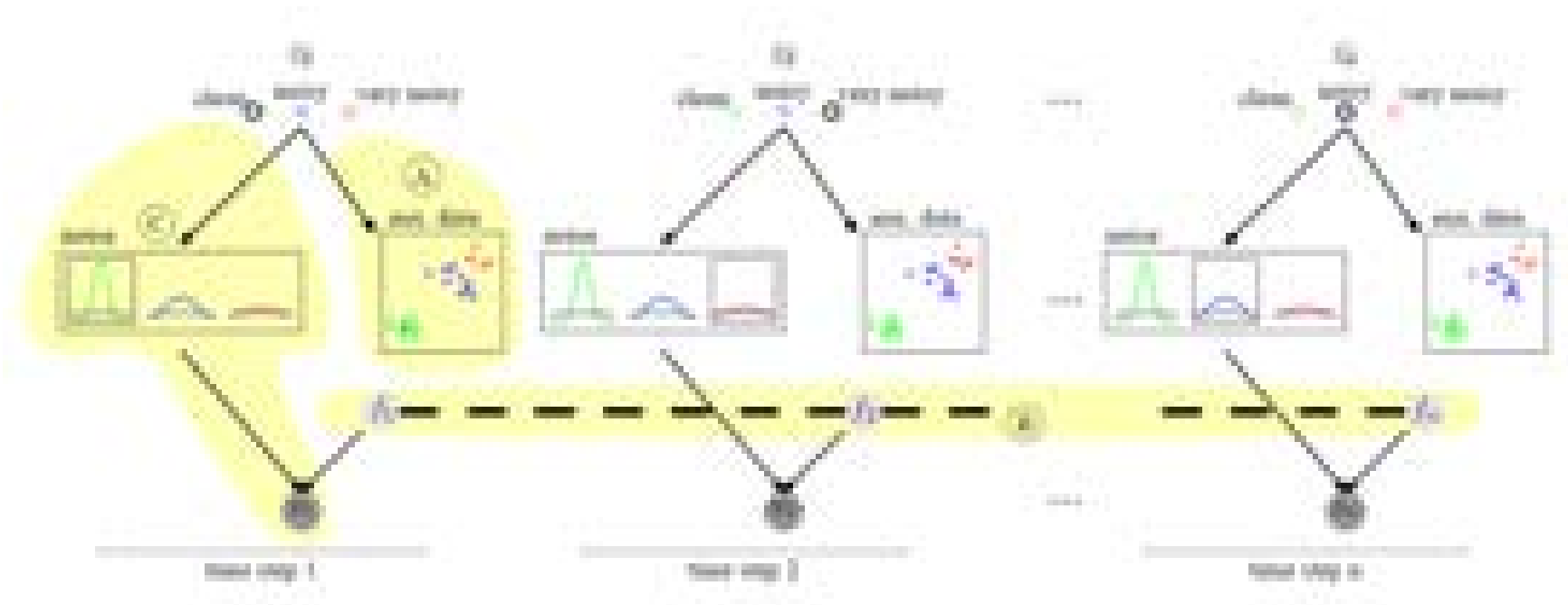


FIG. 2: Heart rate inference model comprised of clustering module (A), Gaussian Process prior (B), and noise model (C) with symbols as defined in the text. Variables g_n denote observed mean heart rate at time point n , f_n is the latent heart rate at this time, and σ_n the status of this data point, i.e., its noise level.

Physiological Priors

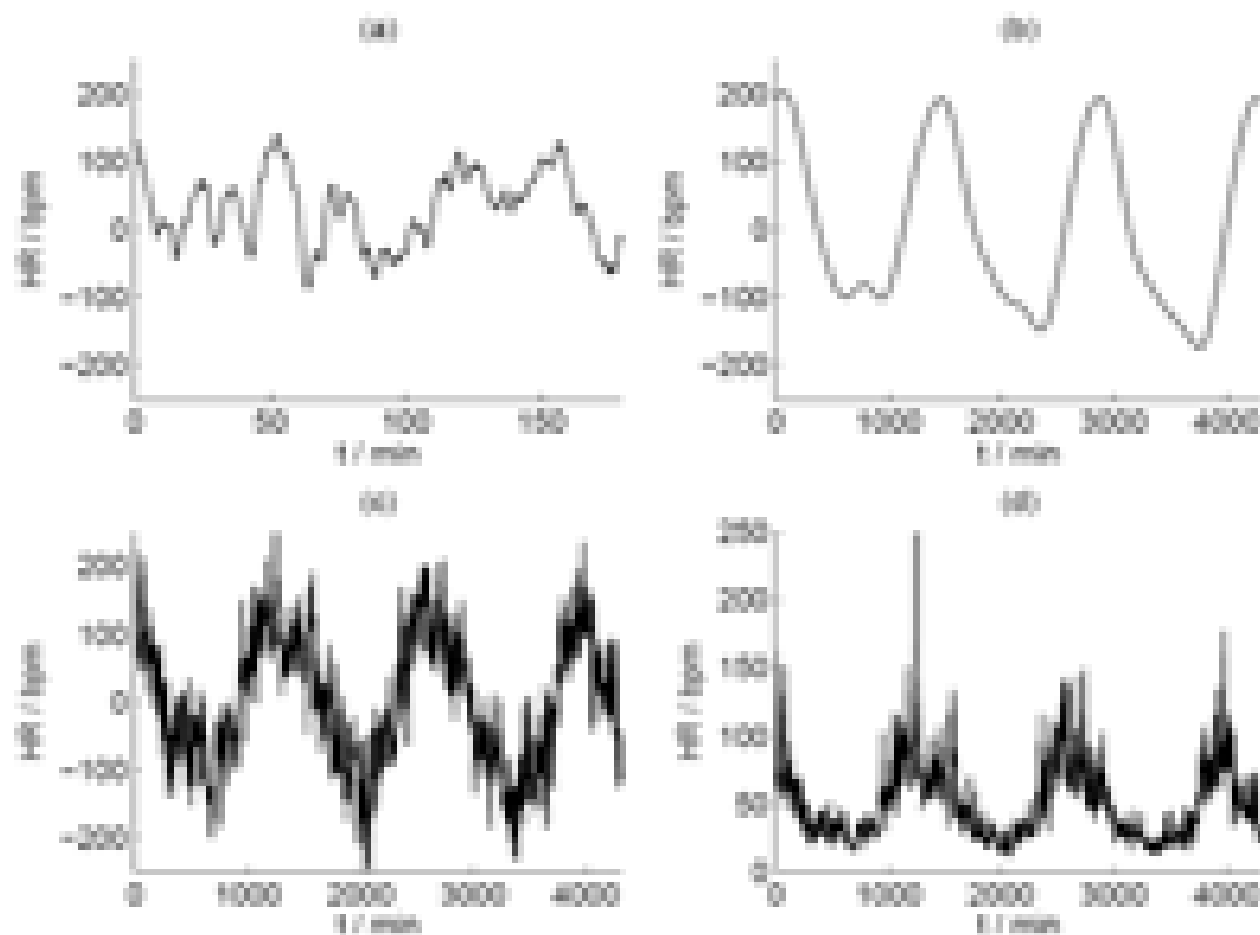
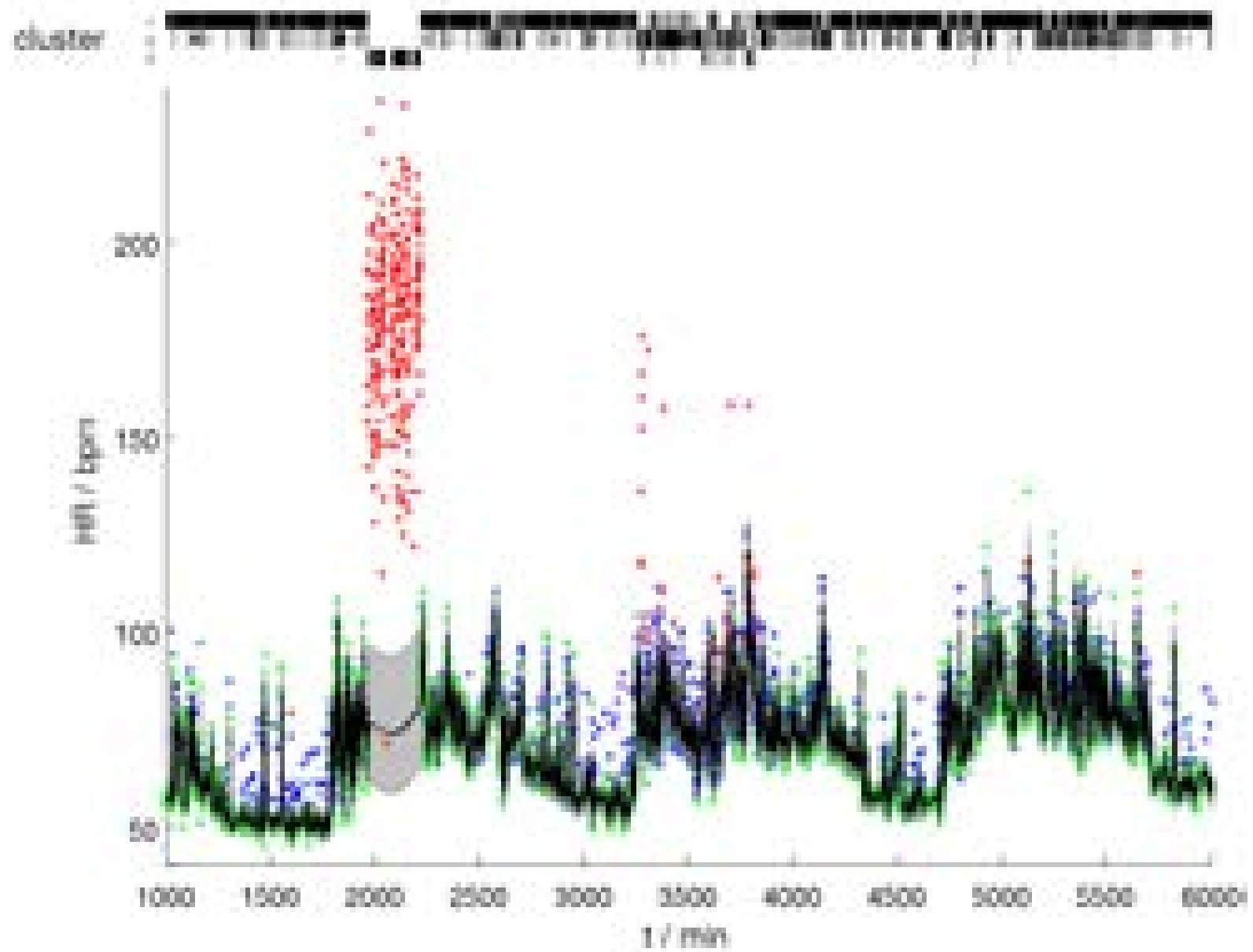


FIG. 4: Samples from the short lengthscale kernel K_S (a), the long lengthscale kernel K_L (b), their sum (c) and the log-transformed CIP price (d) with hyperparameters as defined in the text.



Combined ACC + HR monitoring



Eur J Clin Nutr 59, 561-70, 2005

Original paper / *Eur J Clin Nutr* 2005; 59: 561-70
© 2005 Nature Publishing Group. Printed in the United Kingdom
0954-6794/05 \$30.00

ORIGINAL COMMUNICATION

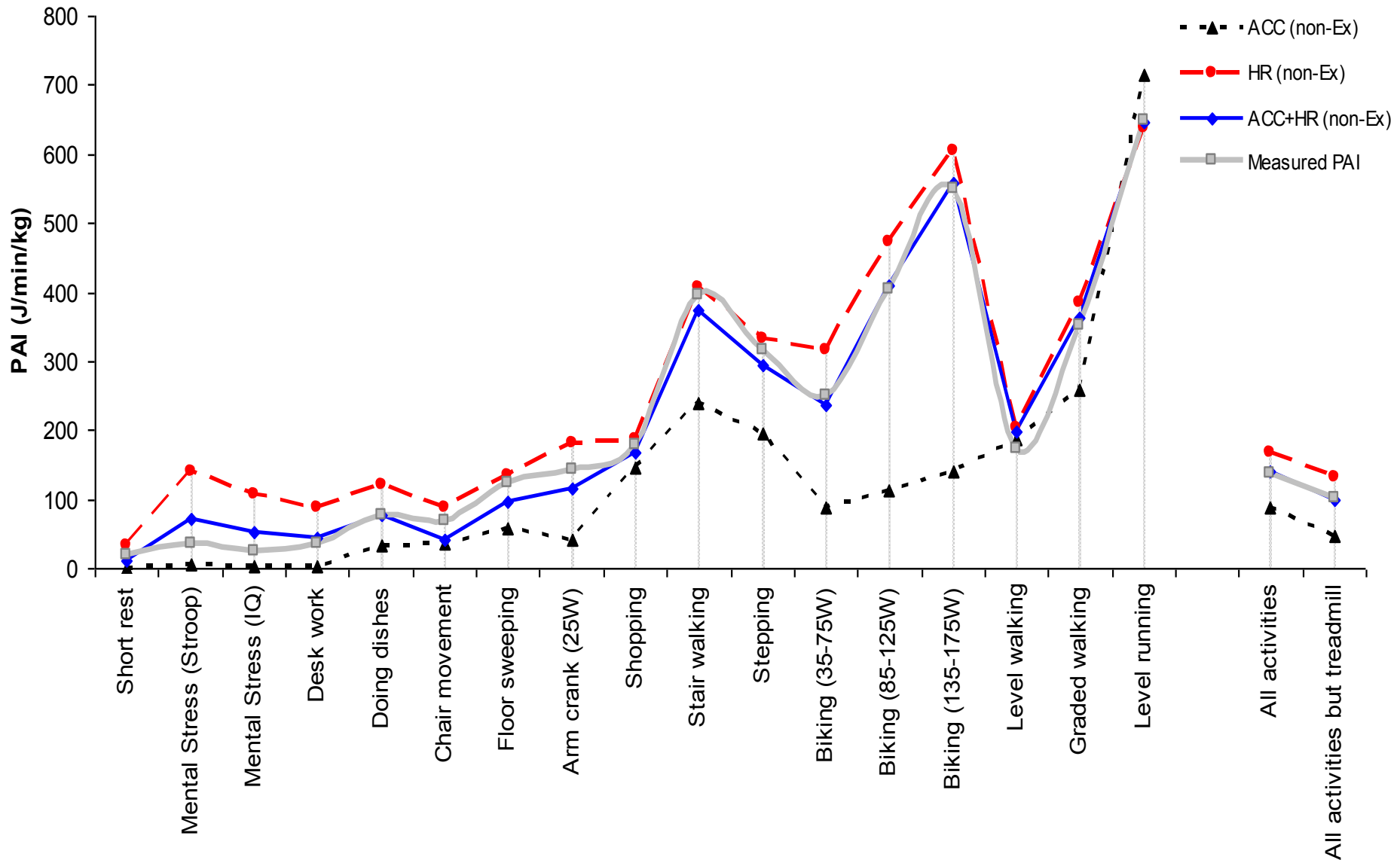
Reliability and validity of the combined heart rate and movement sensor Actiheart

S. Borge¹*, A. Borge², P.W. Franks¹, U. Ekelund¹ and N.J. Wareham¹

¹Unit of Epidemiology (Unit), Institute of Public Health, University of Cambridge, UK, and ²Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark

ACC, HR, and **ACC+HR** during different activities

PAI reference: $\text{breath}^2 \text{VO}_2 + \text{VCO}_2$ (GREY)



Simulated daily-living activities: **Error**

Calibration level

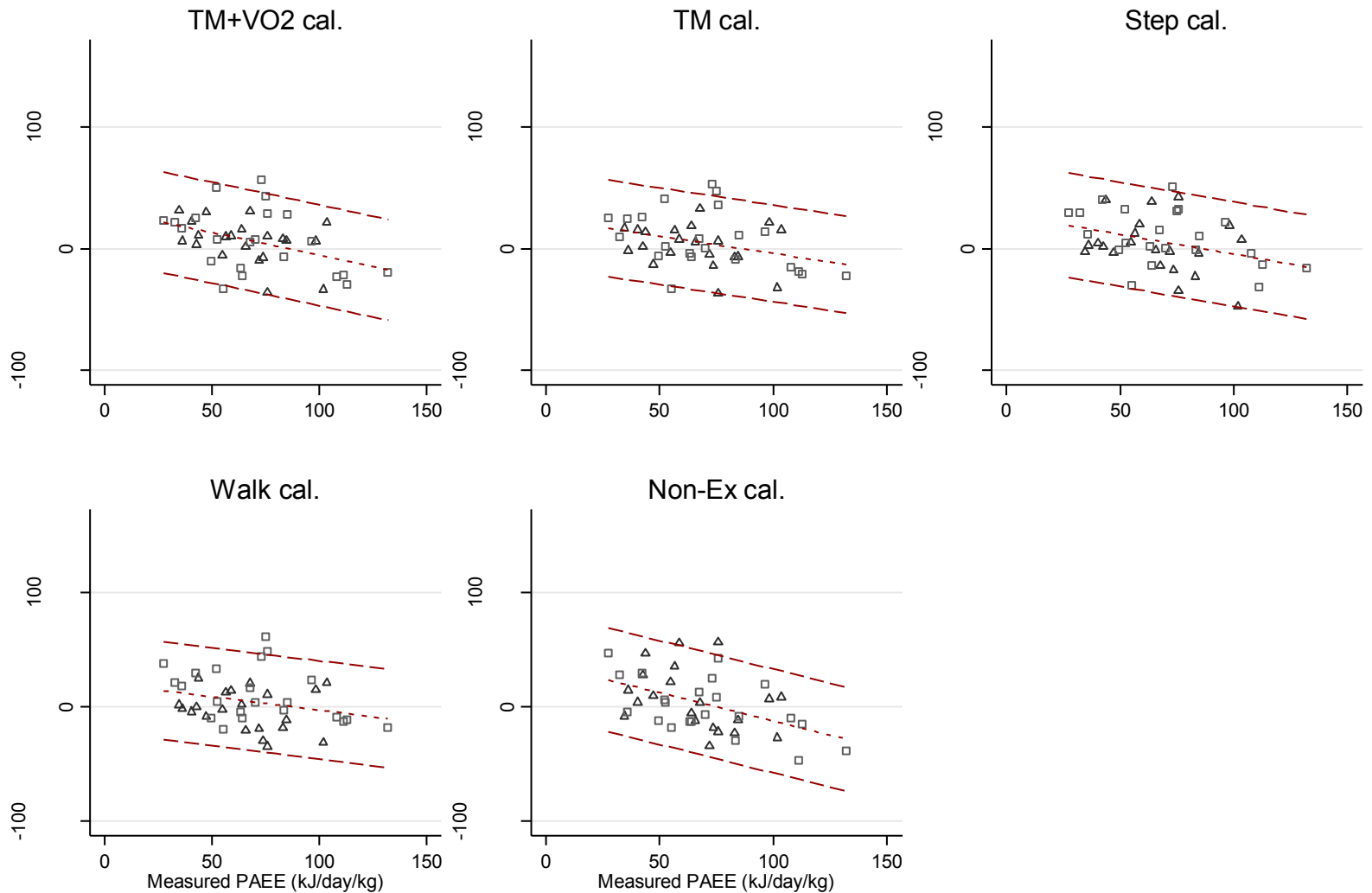
	TM+VO ₂	TM	Step	Walk	Non-Ex
ACC	125 64%	127 65%	130 67%	128 66%	129 66%
Flex HR	56 29%	59 30%	72 37%	69 35%	93 48%
ACC+HR	55 28%	57 29%	58 30%	65 33%	71 36%

Errors are J/min/kg and also expressed relative to measured PAI

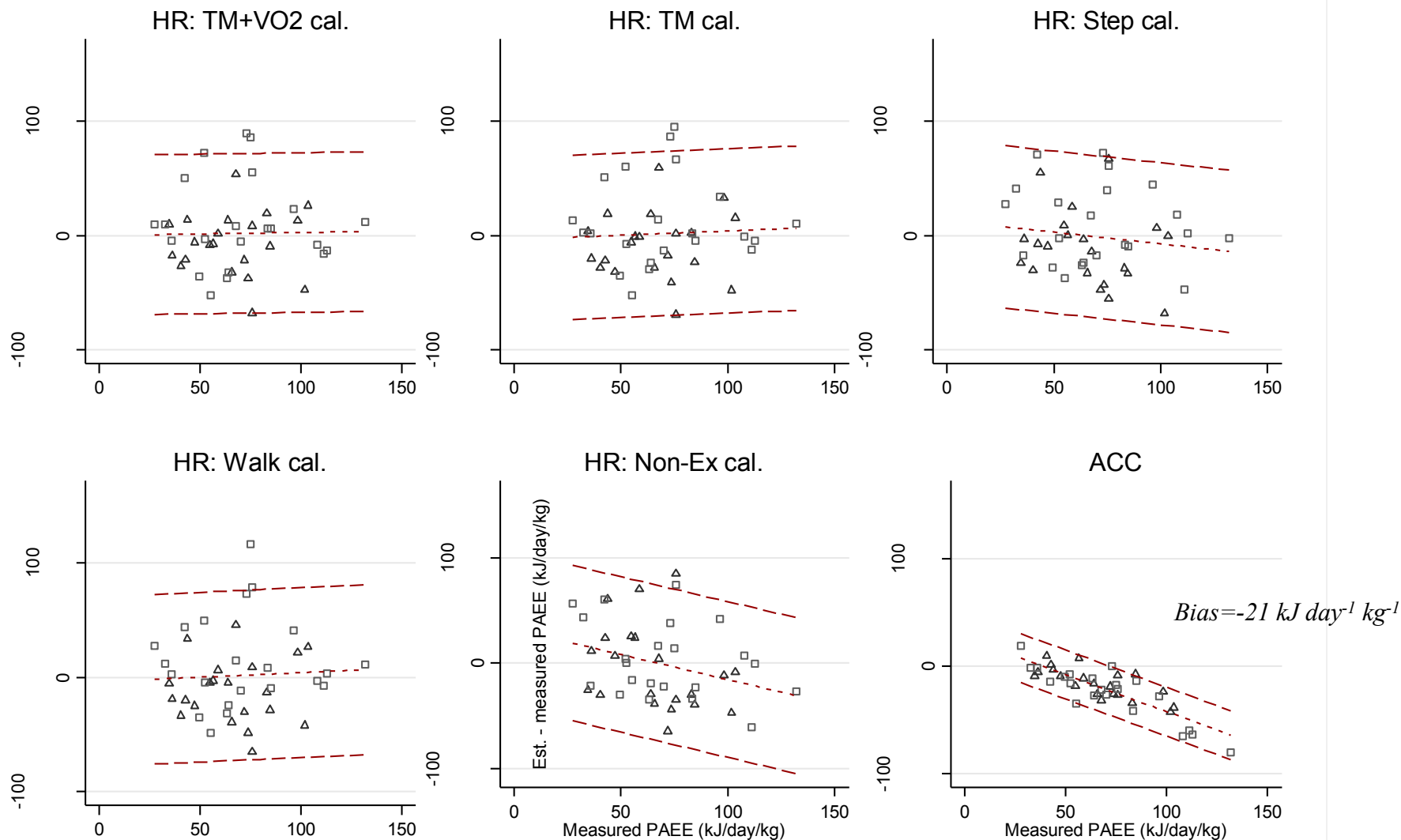
n=38, unpublished

Free-living validation (DLW)

PAEE from branched models



PAEE from singular models



RMS Errors and correlations: Free-living PAEE

	Calibration level				
	TM+VO ₂	TM	Step	Walk	Non-Ex
ACC	-	-	-	-	24 (.52)
Flex HR	33 (.58)	34 (.58)	32 (.57)	34 (.57)	37 (.40)
ACC+HR	21 (.64)	20 (.67)	21 (.66)	21 (.66)	24 (.55)

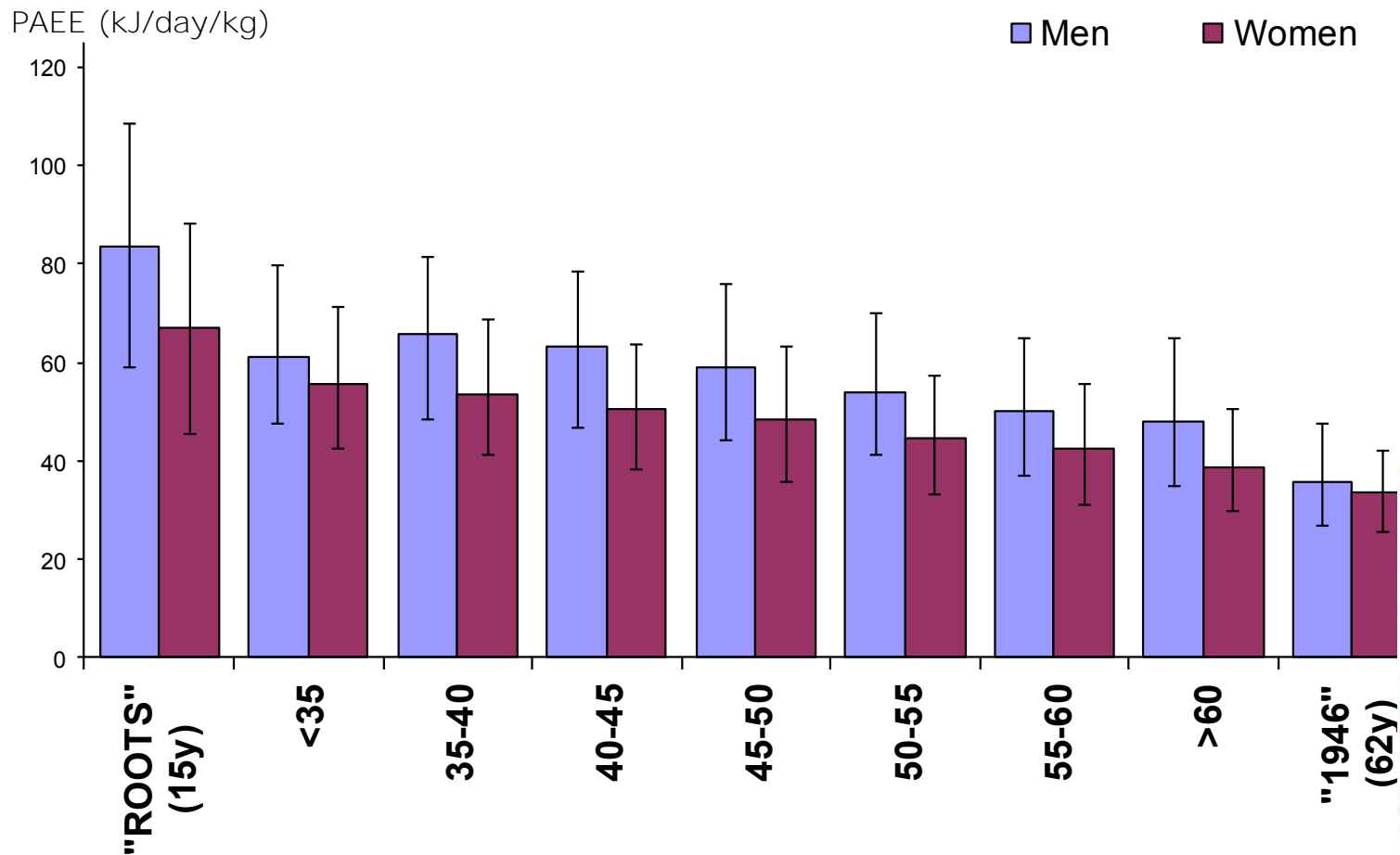
Data are RMSE in kJ/day/kg and correlations (brackets), based on DLW (Scholler method)

DLW-based PAEE validation: UK, Cameroon, Alaska, France

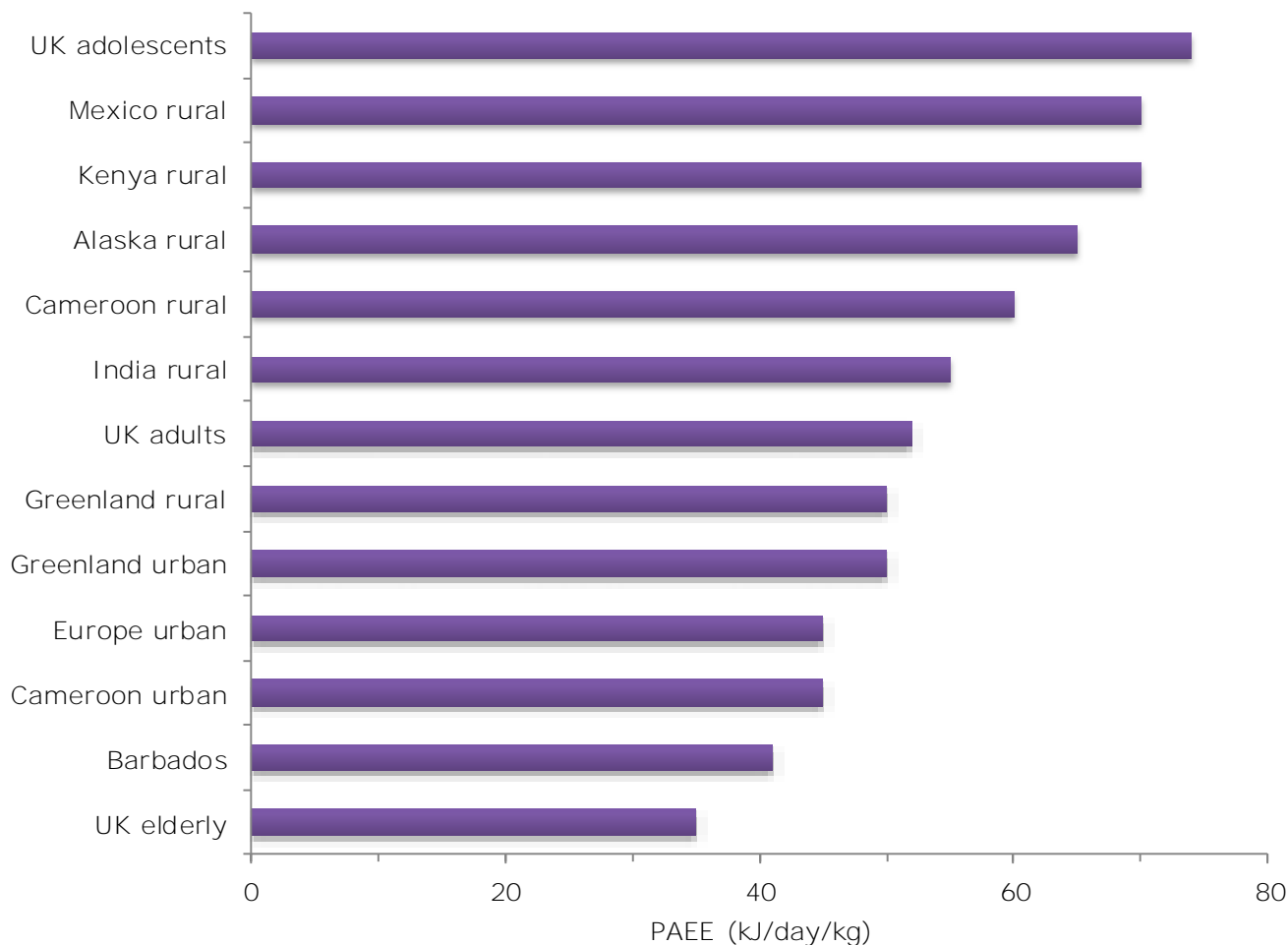
	UK (n=46)		Cameroon (n=33)		Alaska (n=28)		France (n=35 men)	
Calibration	Step	Group*	Step	Group*	Step	Group*	Bike	Group
Mean bias	5 (8%)	5 (8%)	-5 (9%)	-9 (15%)	-2 (3%)	-6 (8%)	-5 (8%)	-8 (13%)
RMSE	21	24	29	30	28	33	14	21
Correlation, r	.66	.55	.40	.39	.62	.43	.81	.62

Data are kJ/day/kg. DLW estimate based on Scholler method. *Population-specific group equations

Physical activity energy expenditure



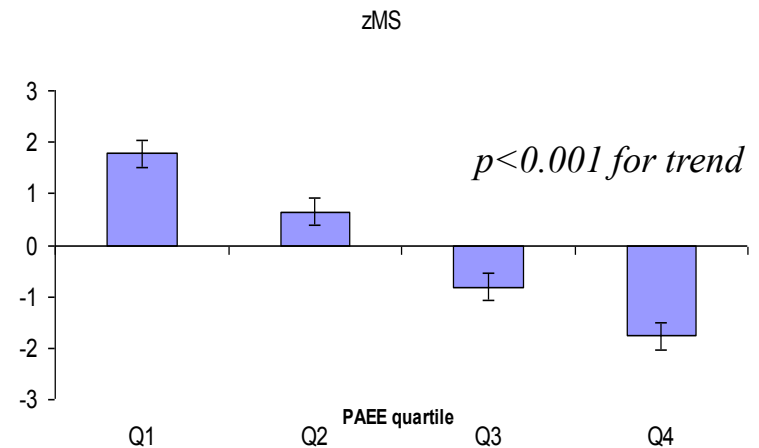
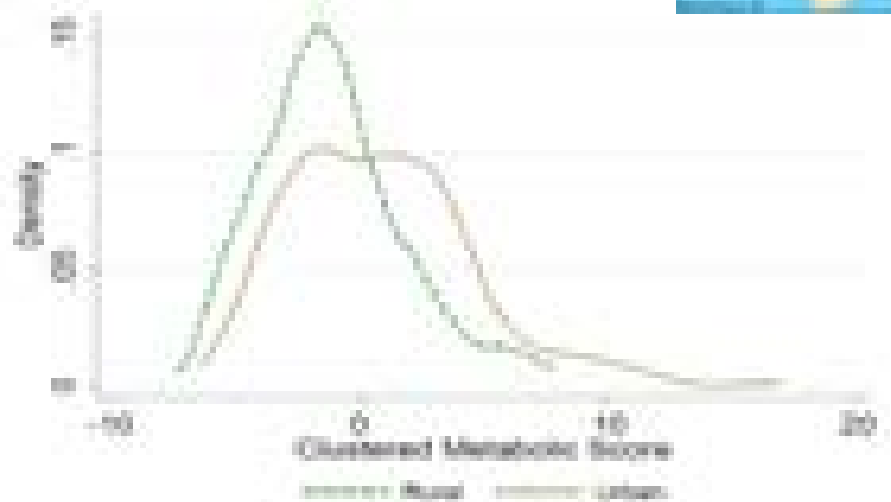
Global variation in activity energy expenditure



Assah et al, 2011+2015
InterAct Consortium, 2012
Christensen et al, 2012a+b
Dahl-Petersen et al, 2013+2014
Collings et al, 2014
Golubic et al, 2014

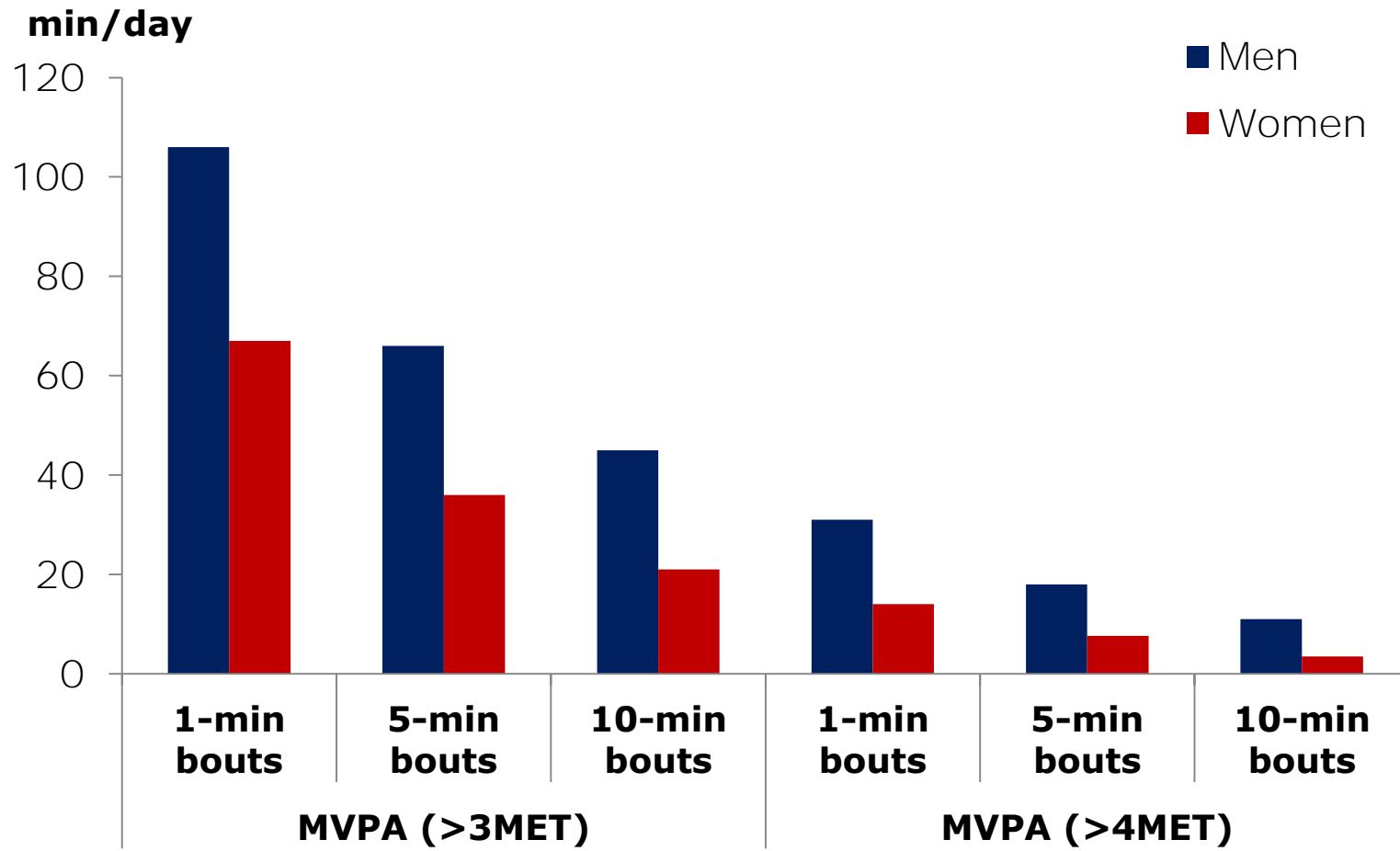
Activity and Clustered Metabolic Risk in Cameroon

Rural - urban differences in 552 adults

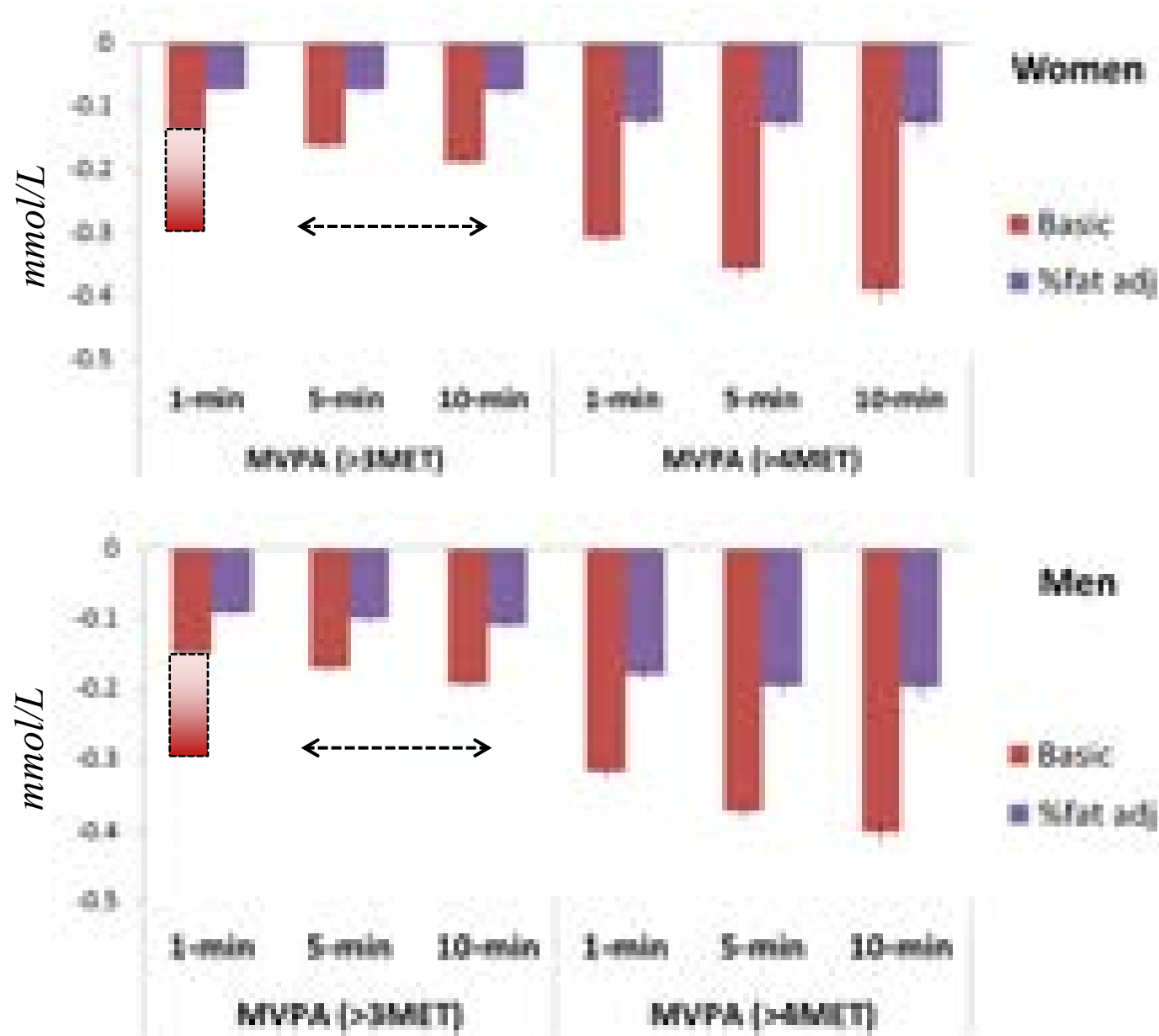


Assah et al, 2011

Physical activity levels by bout duration



Associations with 2-hour glucose



*For every
+30 min/day*

