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A combined heart rate and movement sensor: proof of concept and preliminary testing study

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Objective: Heart rate monitoring has previously been used as a technique for measuring energy expenditure (EE) in field studies. However, the combination of heart rate monitoring with movement sensoring could have theoretical advantages compared to either method used alone. Therefore, this study was undertaken to develop and validate a new combined heart rate monitor and movement sensor instrument (HR + M) for measuring EE.
Methods: The HR + M instrument is a single-piece instrument worn around the chest which records minute-by-minute heart rate and movement. Eight subjects underwent an individual calibration in which EE and heart rate were measured at rest and during a sub-maximal bicycle ergometer test. They then wore the HR + M for 24 hours in a whole-body calorimeter and underwent a standard protocol including periods of physical activity and inactivity. Minute-by-minute heart rate was converted to EE using individual calibration curves with the motion data discriminating between periods of inactivity and activity at low heart rate levels. EE was also calculated using the HRFlex method which relies on heart rate alone. Both estimates of EE were compared to EE measured in the whole-body calorimeter.
Results: The mean percentage error of the HR + M method calculating TEE compared with the gold standard of the calorimeter measurement was 0.00% (95% CI of the mean error −0.25, 1.25). The HRFlex method using the heart rate information alone resulted in a mean percentage error of 16.5% (95% CI of the mean error −0.57, 1.76).
Conclusions: This preliminary test of HR + M demonstrates its ability to estimate EE and the pattern of EE and activity throughout the day. Further validation studies in free-living individuals are necessary.
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Introduction

The development of objective and valid methods for assessing energy expenditure (EE) in population-based studies is an important goal. Such methods would be useful in assessing the strength and nature of the association between physical inactivity and health. They could be employed in monitoring the changes in EE within populations over time and in describing international and cross-cultural differences. Finally they would be of considerable utility in the evaluation of interventions aimed at increasing physical activity (Wareham & Rennie, 1998).

Although the doubly-labelled water method is considered by many to be the gold standard technique, the expense of this method prohibits its use in large studies. Therefore, many researchers have turned to techniques such as heart rate monitoring and movement sensing in an attempt to find cheaper and more feasible ways of measuring EE. Movement sensors, when used alone as an instrument, have limitations. They cannot quantitatively estimate all physical activities, in particular activities such as cycling and rowing, or weight-bearing movement. Movement sensors are not usually waterproof and therefore cannot be worn during swimming, which is one of the most common leisure time activities. These limitations reduce the usefulness of movement sensors alone as instruments to estimate EE in field studies. In addition there are questions about the accuracy of this technique (Fehling *et al*, 1999; Jakicic *et al*, 1999).

Heart rate monitoring has been used in medium-sized epidemiological studies (Wareham *et al*, 1997; Wareham *et al*, 1998) and is a feasible and reliable method for measuring EE, when it is used in combination with measurements of resting metabolic rate (RMR) and an assessment of the individual relationship between EE and heart rate. This HRFlex method has previously been validated against whole-body calorimetry (Spurr *et al*, 1988; Ceesay *et al*, 1989) and against doubly-labelled water (Livingstone *et al*, 1990; Lovelady *et al*, 1993). This technique provides an objective and accurate estimate of EE at a group level, as well as providing a means of describing the pattern of physical activity (Wareham *et al*, 1997). However, there are a number of limitations to this method. This paper describes these limitations and reports the design, development and testing of a combined heart rate and movement sensor that could be of use for measuring EE in population-based studies. This paper also describes a preliminary comparison of the instrument against whole-body

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Contributors: NJ Wareham, T Roswell, D Holburn and SA Jebb developed the original idea for the sensor and designed the testing study. T Roswell and D Holburn were responsible for the production of the prototype. NJ Wareham, SA Jebb and K Rennie supervised the fieldwork in the testing study. All authors contributed to the paper.
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calorimetry to assess accuracy and precision under standardised conditions.

Limitations of HRFlex heart rate monitoring technique

One potential criticism of the heart rate monitoring technique is that it is not possible to differentiate between increases in heart rate due to activity or those due to stress (Haskell *et al*, 1993; Montoye & Taylor, 1984; Meijer *et al*, 1989), especially when the increase in heart rate is modest. This criticism could be addressed by the combination of heart rate monitoring with movement sensoring as small increases in heart rate that are not associated with movement could be detected.

The monitors most commonly used in population-based studies have been designed for athletes and have many functions and settings, and starting the watch receiver is overly complicated. Even though this can be overcome by a detailed explanation to the subject, this is an unnecessary complexity in field studies. In addition, the separation of the transmitter belt and watch receiver which is designed for athletes who wish to observe their heart rates during training, provides the potential for electrical interference from machines, such as microwave ovens or cars (Gretebeck *et al*, 1991), hairdryers and vacuum cleaners (Wareham *et al*, 1997). This requires the heart-rate data to be examined for such readings and either to be replaced by the average of the previous and subsequent values free of interference or for the short segment of data to be removed (Wareham *et al*, 1997). The separation of transmitter and receiver is unnecessary for epidemiological purposes. Indeed, it may be undesirable for the heart rate to be continuously displayed as it creates a greater tendency for people to be aware of their own activity and could provide feedback to the subjects which modulates habitual activity. For these reasons, a single piece monitor which recorded in real time and was simple to start and stop would be an advance.

Therefore, we set out to develop, design and test a new monitor for use in epidemiological studies that would have all the advantages of currently available heart rate monitors, but would be a single instrument piece, avoid electrical interference, record in real time, be easier to start and stop, and would address the criticism of stress/movement differentiation. The new instrument (HR + M) consists of a chest belt containing a heart rate monitor and a simple movement sensor, thus allowing simultaneous measurement of heart rate and movement. It is light, robust and waterproof.

Methods

Design and development of HR + M recorder

The HR + M is capable of recording heart rate and body movement simultaneously for periods of up to five days. It consists of a miniaturised recorder unit and PC interface. The recorder unit is designed to be unobtrusive to normal daily activity, weighing only 100 g, length 14.5 cm, width 3 cm and depth 0.8 cm. It attaches to a standard heart rate monitoring chestband and can be worn under clothing. Power comes from an internal battery designed to last for six months. The recorder contains the heart rate and movement pick-up circuitry along with a microcontroller and non-volatile memory which provide control timing and data recording functions.

The monitor starts automatically as soon as a heart rate is detected. For the first 30 s, a small LED indicates that heart rate detection has commenced and thereafter there is no external indication of the functioning of the monitor. Heart rate is measured from heart electrical activity as in the ECG. This is detected by electrodes in the chestband used to attach the recorder. The signal is amplified and passed to a thresholding circuit which gives a binary output synchronous to the R wave. The movement sensor is housed within the HR + M. It gives a binary output corresponding to 7.5° tilts of the monitor from the horizontal. As the monitor is, in effect, fixed to the chest, this in turn indicates a physical movement of the chest, which occurs in all activities such as walking or cycling. Output from the heart signal and movement sensor is summed over a one minute period and stored in memory and the summation reset. This process continues until the memory is filled or the monitor is reset. The hardware in the HR + M contains an eight bit microcontroller, eight kilobytes of non-volatile memory and analogue electronics for heart and physical activity detection. Communications with the PC are effected by connecting the monitor to a custom designed interface. Communication software has been written to enable data download, setting of the monitor internal clock and reprogramming of the microcontroller.

Recruitment of volunteers and individual calibration of energy expenditure and heart rate

Eight subjects (five men and three women) were recruited from Cambridge University. In order to determine the O_2 consumption−heart rate relationship for each subject, a calibration test was undertaken using the standard HRFlex protocol (Wareham *et al*, 1997; Wareham *et al*, 1998). Heart rate, minute volume and expired air O_2 concentration were recorded with the subject lying prone, seated and while cycling on a cycle ergometer. Inspired and expired O_2 concentrations were measured using an O_2 analyser (PK Morgan Ltd, Rainham, Gillingham, Kent, UK) calibrated daily using 100% N_2 and fresh air as standard gases. Ambient room temperature and barometric pressure were also recorded. Subjects cycled at 50 rev/min at 0 W, 37.5 W, 75 W and 125 W for five minutes each. Recordings were made in the final three minutes of each workload level. The O_2 consumption, corrected for standard temperature and pressure, was calculated and energy expenditure computed at each time point as O_2 consumption (ml/min) $\times$ 20.35 (Consolazio *et al*, 1963). Ethical approval for the study was obtained from the MRC Dunn Nutrition Unit Ethical Committee.

Mean resting EE was taken as the average of the lying and sitting values. In the original description of the HRFlex method (Spurr *et al*, 1988) a single linear regression line was used to predict EE from heart rate above an empirical flex point, defied as the average of the highest pulse rate at rest and the lowest on exercise. For this study, however, a segmented calibration was used producing two slopes at low and moderate-high activity respectively. This required the definition of two flex points. Flex1 heart rate was calculated as the lowest resting heart rate and Flex2 heart rate was calculated as the lowest heart rate recorded during the cycling at 37.5 W (Figure 1). The slope and intercept of two regression lines were calculated using the least squares method. The first line between the two flex points was calculated using the exercise points during the cycling up to 37.5 W. The second line was calculated using the exercise

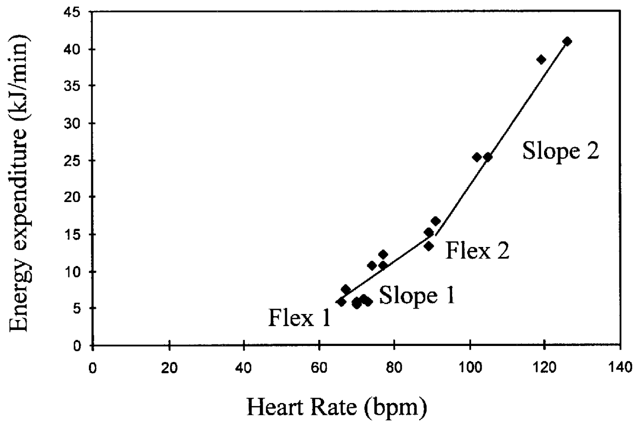

Figure 1 Individual calibration of EE against heart rate for the HR + M method.

points above Flex2. These calculations were undertaken using an SPSS syntax file (Statistical Package for the Social Sciences, SPSS Inc, Chicago, IL, USA).

Measurement of EE and exercise protocol

Each subject spent 24 h in a whole-body calorimeter at the MRC Dunn Clinical Nutrition Centre wearing the HR + M. Simultaneous measurement of HR, movement and VO_2 were made during this period. Each subject followed the same standardised protocol comprising periods of rest, exercise and sedentary activities such as reading and watching television. The whole-body calorimeter is designed as a comfortable bed-sitting room 3.5 m × 2.8 m × 2.1 m in dimension. Air is recirculated at 20 m^3/min to mix the subject's expired air with room air to produce uniform room air composition. Temperature is kept constant at 23 ± 0.5°C and the room is ventilated at a rate of 200 l/min with fresh air drawn from outside the building. The ventilation was measured as the air entered the chamber, by a type 2100 Rotameter (KDG Mowbray, Slough, UK) and a vortex-shedding flowmeter type VL512 (Delta Controls, West Molesey, UK). Samples of fresh air and ventilating air were drawn for analysis. The moisture content of the samples was measured (Dewpoint analyser type 1100ap, General Eastern, Watertown, MA, USA), then dried by PermPure membrane dryers (Perma-Pure Products Inc., Toms River, NJ, USA) before analysis of oxygen and carbon dioxide (Paramagnetic O_2 analysers types 184 and 1440 and infra-red CO_2 analysers type 1510; Servomex, Crowborough, UK). Data from the analysers were digitised (Systems voltmeter type 7062 with 18 channel scanner, Solartron, Farnborough, UK) and logged onto a personal computer through a Measurement Co-processor (Hewlett Packard, Palo Alto, CA, USA). Data were logged every five minutes throughout the study. Fresh air samples were analysed every 30 minutes while every three hours, analyser calibrations were checked using O_2-free N_2 for zeros, 1% CO_2 in air for CO_2 span and fresh air for O_2 span.

Oxygen consumption and carbon dioxide production were calculated using the expressions derived by Brown *et al* (1984). Energy substrate oxidation rates were calculated from gas exchanges using the expressions of Murgatroyd *et al* (1993), and the values for the respiratory quotients and energy equivalents of oxygen for each substrate proposed by Elia and Livesey (1992). The measurements made by the calorimeter were calculated as 30 minute averages of energy expenditure (kJ/min).

Simultaneous estimation of energy expenditure by HR + M and HRFlex methods

At the end of the period in the calorimeter, the HR + M belt was removed from the subject and using a custom interface, the readings were downloaded into a personal computer. Readings from the movement sensor were expressed as movement counts per minute. The individual calibration data were used to calculate EE. This computation depended on the heart rate for that minute. If the heart rate was below the Flex1 level, estimated EE equalled resting EE. If the heart rate was above Flex1 but below Flex2 and movement was less than 40 counts/min, then the EE was again estimated to be equal to resting EE. If, however, the heart rate was above Flex1 level but below Flex2 level and movement was greater than 40 counts/min, the intercept and slope from the first regression line were used to calculate EE. If the heart rate was greater than Flex 2, the intercept and slope from the second line were used. The HRFlex method was also used to calculate EE using the heart rate data alone. For this calculation, the single linear regression line and Flex point was used. If the heart rate was below the Flex level, estimated EE equalled resting EE. If the heart rate was greater than the Flex point the intercept and slope for the single regression line were used. The 40 counts/min threshold was selected because in pre-testing it discriminated between periods of movement and inactivity.

Estimated EE from the HR + M method was then averaged for each 30 minute period (kJ/min). EE directly measured in the calorimeter and estimated by the HR + M and the original HRFlex method for the 12-hour day period was calculated for each subject to compare total EE. The percentage error of the HR + M and HRFlex methods compared to the calorimeter EE was calculated for each subject.

Results

The selected characteristics of the subjects are shown in Table 1. The mean age was 31.3 y (range 23–54 y), mean weight 71.8 kg (range 47–94 kg) and mean height 174.2 cm (range 157–188 cm). No subject was obese (mean BMI 23.5 kg/m^{-2}). Figure 2 shows an example of heart rate and movement data from one day in the calorimeter. Both these measurements follow similar patterns throughout the day. The peaks of exercise can be clearly seen in both graphs, and the heart rate data displays the proportionate increased level of energy required for the particular exercise.

Table 1 Baseline characteristics of subjects ($n = 8$)

Subject	*Sex*	*Age (y)*	*Weight (kg)*	*Height (cm)*	*BMI (kg/m²)*
1	male	54	69.5	178.9	21.7
2	female	27	47.5	157.8	19.1
3	female	23	52.0	173.4	17.3
4	male	23	94.2	188.4	26.5
5	male	35	78.5	174.8	25.7
6	female	24	75.0	166.6	27.0
7	male	27	84.0	174.0	27.7
8	male	37	73.5	180.0	22.7

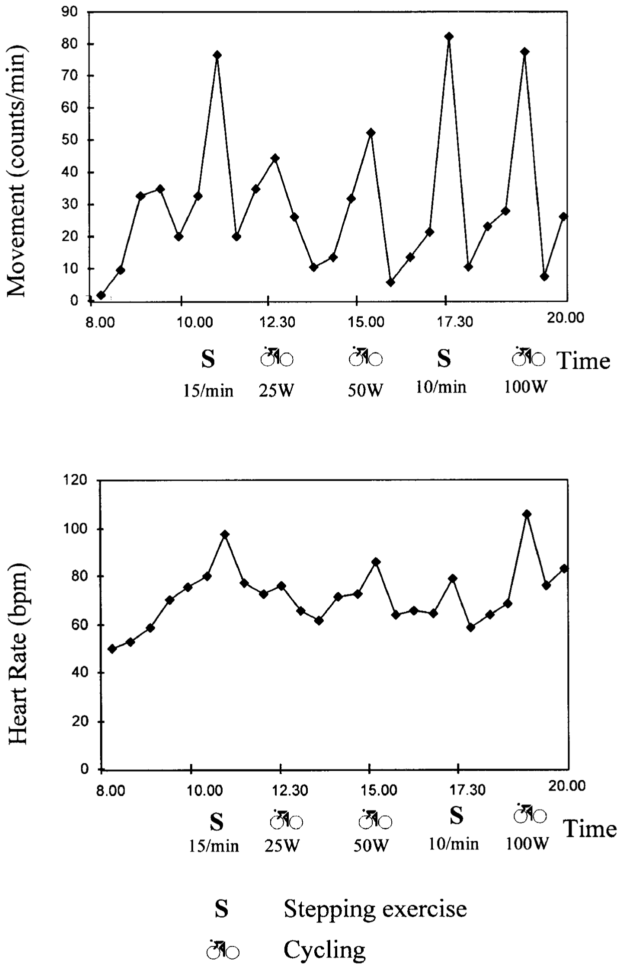

Figure 2 Simultaneous movement and heart rate measured in subject 4 over 12-h study period with exercise protocol as indicated.

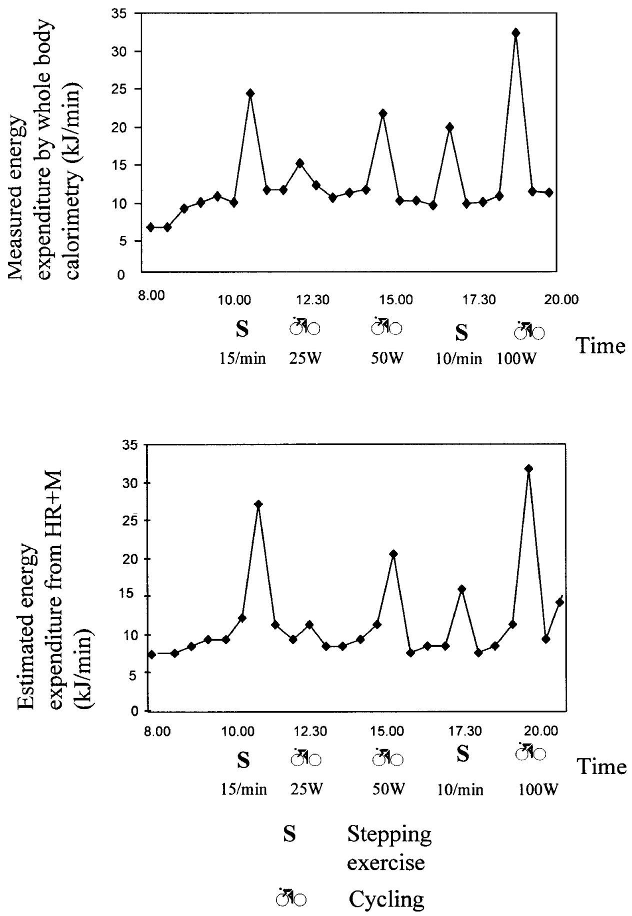

Figure 3 Simultaneous 30-minute EE (kJ/min) calculated in whole body calorimetry and from HR + M in subject 4 over 12-h study period.

Figure 3 shows the EE levels from one day calculated from the whole-body calorimeter and the HR + M method. These data show the ability of the HR + M not only to estimate EE, but also to accurately show the pattern of EE and activity throughout the day.

The percentage error of the HR + M EE estimates from the calorimeter measures ranged from −22% to + 19%. The mean percentage error of the HR + M method was 0.00% and 16.5% for the HRFlex method (Table 2). The standard deviation of the percentage error between total EE estimated from the HR + M (EE_{HR+M}) and measured by calorimetry (EE_{CAL}) was 12.5%. The same figure for total EE estimated from the HRFlex method (EE_{HR}) was 30.3%.

In order to estimate the degree of misclassification of low intensity activity or stress-induced tachycardia, we computed the amount of time for each subject that would have been classified as activity by the HRFlex method, but which was deemed to be inactivity by the HR + M technique. We also computed the converse. In this study, an average of 134.8 min (s.d. 108.41 min) that were classified as inactivity by the HR + M method, would have been classified as activity by the HRFlex method using heart rate alone. Conversely, an average of 67.4 min (s.d. 74.4 min) classified as activity by the HR + M method, would have been classified as inactivity by the HRFlex method. These periods account for up to 43% (range 3−43%) and 27% (range 2−27%) of the subject's daily physical activity time respectively (Table 3).

Discussion

The HR + M is the first one-piece instrument that is able to measure both heart rate and movement, as previous studies have used separate instruments to record these two measurements (Haskell *et al*, 1993; Meijer *et al*, 1989; Moon & Butte, 1996). The HR + M is less obtrusive than current heart rate monitors and has no external display, reducing the possibility for subjects to be overaware of their activity, which may influence behaviour. It has no external switches, simplifying the process of starting the watch and reducing the time required for the explanation of the HR + M technique to each subject.

Advantages of combined sensor

In this small preliminary study, the use of movement sensoring in combination with heart rate reduced the overall error of the two instruments. However, there was still a range of error between EE measured by whole-body calorimetry and estimated by the prototype at the individual level. Heart rate monitoring is not subject to the errors of movement sensoring, such as detecting the level of activity during resistance exercise, such as cycling and swimming. Likewise, movement sensoring complements heart rate

Table 2 Comparison of total EE in 12-h period measured by HRFlex method (TEE_{HR}) and total EE measured by HR + M (TEE_{HR+M}) with simultaneous whole-body calorimetry (TEE_{CAL}) ($n = 8$)

Subject	TEE_{CAL} (kJ)	TEE_{HR} (kJ)	$TEE_{HR}-TEE_{CAL}$ (kJ)	$TEE_{HR}-TEE_{CAL}$ (as % of TEE_{CAL})	TEE_{HR+M} (kJ)	$TEE_{HR+M}-TEE_{CAL}$ (kJ)	$TEE_{HR+M}-TEE_{CAL}$ (as % of TEE_{CAL})
1	6234.5	7689.0	1454.5	+23.3	7415.0	1180.4	+18.9
2	5123.0	4484.0	−639.0	−12.5	4522.1	−609.9	−11.7
3	5396.1	7630.6	2234.5 + 41.4	+41.4	5652.1	256.0	+4.7
4	7863.1	9584.1	1721.0	+21.9	8434.2	571.1	+7.3
5	7022.4	5976.4	−1046.0	−14.9	5500.9	−1521.5	−21.7
6	6395.5	6998.2	602.7	+9.4	6414.6	19.1	0.0
7	7063.8	6412.0	−651.8	−9.2	6786.9	−276.9	−3.9
8	6589.2	11380.9	4809.3	+72.7	7024.1	434.9	+6.6
Mean (s.d.)			1060.6 (1945.4)	+16.5 (30.2)		7.78 (821.7)	0.0 (12.5)

Table 3 Comparison of activity and inactivity classification between the HRFlex method and the HR + M method at low intensity activity levels

Subject no	*HR + M activity Reclassification*[a] (% of 12-h period)	*HR + M inactivity Reclassification*[b] (% of 12-h period)
1	29 (4.0)	71 (9.9)
2	174 (24.2)	22 (3.1)
3	15 (2.1)	280 (38.9)
4	16 (2.2)	148 (20.6)
5	78 (10.8)	82 (11.4)
6	18 (2.5)	139 (19.3)
7	192 (26.7)	28 (3.9)
8	17 (2.4)	308 (42.8)
Mean	67.4 (9.4)	134.8 (18.7)
(s.d.)	74.5 (10.4)	108.4 (15.1)

[a]Number of minutes classified as inactivity by HRFlex method and classified as activity by HR + M method.
[b]Number of minutes classified as activity by HRFlex method and classified as inactivity by HR + M method.

monitoring, since it allows differentiation between increased heart rate caused by physical activity and that caused by other influences such as caffeine and stress. This study was limited by the number of subjects which was smaller than the number used in calorimeter validation studies ($n = 22$ (Spurr *et al*, 1988) and $n = 20$ (Ceesay *et al*, 1989)). However, despite this the mean percentage error of the EE estimated by the HR + M and that measured by the calorimeter method showed an unbiased estimate of group EE of 0.00% (s.d. 12.5) when compared with the HRFlex method which resulted in a mean percentage error of 16.5% (s.d. 30.3). The HR + M method provided a more precise estimate of group EE as the standard deviation of the mean percentage error was smaller than the HRFlex method. This improved precision with the HR + M method is also relative to previously published percentage error estimates from the HRFlex method (Spurr *et al*, 1988) (EE_{HR}) *vs* calorimetry, where the standard deviation was 17.9%. In larger study groups with greater power, it can be expected that the confidence intervals of the mean percentage error will decrease.

Other studies involving heart rate monitoring and movement sensoring

This is the first study to use heart rate monitoring and movement sensoring simultaneously and jointly to estimate EE with a short calibration test (45 min). Moon and Butte (1996) used heart rate monitoring and movement sensoring to predict EE, with movement and heart rate threshold levels calculated for each individual to determine periods of activity and inactivity. They reported a mean error of −4.6% (s.d. 4.5) between their regression model prediction of oxygen consumption using heart rate and movement and the measurement of consumption by a whole-body calorimeter. However, they did not measure heart rate and movement with a one-piece instrument, but rather by telemetry and with a vibration sensor worn on the leg. In addition, the estimates of oxygen consumption were based on a 24-h calibration period for each subject in a whole-body calorimeter. Such a calibration test period is not feasible in large population-based studies. The Meijer *et al* (1989) study reported the concurrent recording of heart rate and movement, but estimated EE separately from the two methods. Two studies have used multiple regression to predict oxygen uptake from heart rate and motion sensors (Haskell *et al*, 1993; Luke *et al*, 1997). However, only estimations of EE from exercise tests or specific simulated daily activities performed in a laboratory were made. These studies concluded that motion sensors did not improve the prediction of EE in strenuous exercise tests, but did improve the prediction in activities at lower heart rates. Correlations using both heart rate and motion sensors for activities at low-to-moderate heart rates compared to heart rate alone increased by up to 0.13 on an individual basis (Luke *et al*, 1997). It is at these lower heart rates, which make up the majority of most subjects' days, that the combination of heart rate monitoring and movement sensoring yields the greatest advantages.

Appropriate validation studies

Since the HR + M instrument was designed to be used in free-living conditions, a more informative validation would now be with doubly-labelled water. This method has been used in studies to validate heart rate monitoring in adults (Lovelady *et al*, 1993; Livingstone *et al*, 1990; Racette *et al*, 1995) and children (Emons *et al*, 1992; Maffeis *et al*, 1995; Livingstone *et al*, 1992). In adult populations, the mean percentage errors reported in these validation studies (−5.2% ± 10.8 (Racette *et al*, 1995), 2% ± 17.9 (Livingstone *et al*, 1990), −5.8% ± 13 (Lovelady *et al*, 1993)) are comparative to this study (0.00%, s.d. 12.5). In addition, future validation studies would involve the use of population-based volunteers undertaking their usual activities rather than a fixed activity protocol as in this study.

Conclusion

We conclude that we have successfully developed a combined instrument using heart rate monitoring and movement sensoring that fulfills our five key design attributes. Our preliminary testing suggests that the combined sensor may have the expected advantages over heart rate monitoring alone, an hypothesis to be tested in future validation studies against doubly-labelled water. We believe that such an instrument could be of use in population-based studies and may prove to be a simpler and more accurate alternative to current instruments used to estimate physical activity EE.

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References

Brown D, Cole TJ, Dauncey MJ, Marrs RW, Murgatroyd PR (1984): Analysis of gaseous exchange in open circuit indirect calorimetry. *Med. & Biol Eng. & Comput.* **22**, 333–338.

Ceesay SM, Prentice AM, Day KC, Murgatroyd PR, Goldberg GR, Scott W (1989): The use of heart rate monitoring in the estimation of energy expenditure: a validation study using indirect whole-body calorimetry. *Br. J. Nutr.* **61**, 175–186.

Consolazio CF, Johnson RE, Pecora LJ (1963): *Physiological measurements of metabolic functions in man*. New York: McGraw Hill.

Elia M & Livesey G (1992): Energy expenditure and fuel selection on biological systems: the theory and practise of calculations based on indirect calorimetry and tracer methods. In: *Control of eating, energy expenditure and the bioenergetics of obesity*. AP Simopoulos (ed.), Karger, Basel, pp 68–131.

Emons H, Groenenboom D, Westerterp K, Saris W (1992): Comparison of heart rate monitoring combined with indirect calorimetry and the doubly labelled water method for the measurement of energy expenditure in children. *Eur. J. Appl. Physiol.* **65**, 99–103.

Fehling PC, Smith DL, Warner SE, Dalsky GP (1999): Comparison of accelerometers with oxygen consumption in older adults during exercise. *Med. Sci. Sports Exerc.* **31**(1), 171–175.

Gretebeck RJ, Montoye HJ, Ballor D, Montoye AP (1991): Comment on heart rate recording in field studies. *J. Sports Med. Phys. Fitness.* **31**, 629–631.

Haskell WL, Yee MC, Evans A, Irby PJ (1993): Simultaneous measurement of heart rate and body motion to quantitate physical activity. *Med. Sci. Sports Exerc.* **25**, 109–115.

Jakicic JM, Winters C, Lagally K, Ho J, Robertson RJ, Wing RR (1999): The accuracy of the TriTrac-R3D accelerometer to estimate energy expenditure. *Med. Sci. Sports Exerc.* **31**(5), 747–754.

Livingstone MBE, Coward WA, Prentice AM, Davies PSW, Strain JJ, McKenna PG, Mahoney CA, White JA, Stewart CM, Kerr M-JJ (1992): Daily energy expenditure in free-living children: comparison of heart-rate monitoring with the doubly labeled water method. *Am. J. Clin. Nutr.* **56**, 343–352.

Livingstone MBE, Prentice AM, Coward WA, Ceesay SM, Strain JJ, McKenna PG, Nevin GB, Barker ME, Hickey RJ (1990): Simultaneous measurement of free-living energy expenditure by the doubly labeled water method and heart-rate monitoring. *Am. J. Clin. Nutr.* **52**, 59–65.

Lovelady C, Meredith C, McCrory M, Nommsen L, Joseph L, Dewey K (1993): Energy expenditure in lactating women: a comparison of doubly labelled water and heart-rate-monitoring methods. *Am. J. Clin. Nutr.* **57**, 512–518.

Luke A, Maki K, Barkey N, Cooper R, McGee D (1997): Simultaneous monitoring of heart rate and motion to assess energy expenditure. *Med. Sci. Sports Exerc.* **29**(1), 144–148.

Maffeis C, Pinelli L, Zaffanello M, Schena F, Iacumin P, Schutz Y (1995): Daily energy expenditure in free-living conditions in obese and non-obese children: comparison of doubly-labelled water method and heart-rate monitoring. *Int. J. Obes.* **19**, 671–677.

Meijer G, Westerterp K, Koper H, Ten Hoor F (1989): Assessment of energy expenditure by recording heart rate and body acceleration. *Med. Sci. Sports Exerc.* **21**(3), 343–347.

Montoye P & Taylor H (1984): Measurement of physical activity in population studies. *Hum. Biol.* **56**, 195–216.

Moon JK & Butte NF (1996): Combined heart rate and activity improve estimates of oxygen consumption and carbon dioxide production rates. *J. Appl. Physiol.* **81**(4), 1754–1761.

Murgatroyd PR, Sonko BJ, Wittekind A, Goldberg GR, Ceesay SM, Prentice AM (1993): Non-invasive techniques for assessing carbohydrate flux. I. Measurement of depletion by indirect calorimetry. *Acta Physiol. Scand.* **147**, 91–98.

Racette SB, Schoeller DA, Kushner RF (1995): Comparison of heart rate and physical activity recall with doubly labeled water in obese women. *Med. Sci. Sports Exerc.* **27**, 126–133.

Spurr GB, Prentice AM, Murgatroyd PR, Goldberg GR, Reina JC, Christman NT (1988): Energy expenditure from minute-by-minute heart-rate recording: comparison with indirect calorimetry. *Am. J. Clin. Nutr.* **48**, 552–559.

Wareham NJ, Hennings SJ, Byrne CD, Hales CN, Prentice AM, Day NE (1998): A quantitative analysis of the relationship between habitual energy expenditure, fitness and the metabolic cardiovascular syndrome. *Br. J. Nutr.* **80**, 235–241.

Wareham NJ, Hennings SJ, Prentice AM, Day NE (1997): Feasibility of heart rate monitoring to estimate total level and pattern of energy expenditure in a population-based epidemiological study. *Br. J. Nutr.* **78**, 889–900.

Wareham NJ, Rennie KL (1998): The assessment of physical activity in individuals and populations: Why try to be more precise about how physical activity is assessed. *Int. J. Obes.* **22**(Suppl 2), S30–S38.