Methods to Assess Physical Activity with Special Reference to Motion Sensors and Accelerometers

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***Abstract*—Motion sensors may be applied for the assessment of physical activity. This paper reviews the evolution of these instruments from the mechanical pedometer to the electronic accelerometer. We conclude that for accurate assessment of physical activity under free living conditions the recently introduced accelerometer looks most promising, although little information was available regarding the reliability of these instruments. Subsequently, reliability of an accelerometer with a three-directional sensor was examined. Intrainstrument variation in a bench test was less than 8% during four measurements over a week. Interinstrument variation during treadmill experiments while subjects wore two accelerometers at the same time was on average 22% and was not improved after adjustment for differences found in the bench test. Reproducibility in the treadmill experiment was approximately 76, 85, and 95% at 3, 5, and 7 km/h, respectively. Bench testing revealed that the sensitivity of a piezoelectric element is prone to shifts, probably due to mechanical, electromagnetic, and/or temperature shock, which may be encountered during outdoor application. However, the relevance of the bench test in this study may be questioned, as results did not correspond with the findings in subjects. This needs further investigation.**

I. Introduction

PHYSICAL ACTIVITY, being an important part of human behavior, may be related to various aspects of health and disease. The study of these relationships is difficult and cumbersome mostly due to the complex nature of physical activity and the resulting difficulties in measuring it. For a long time, observational techniques were the only reliable methods to get an impression of physical activity. However, this approach is costly, not free of the subjective judgement of the observer and not of any use if larger groups must be studied. Therefore, there is a need for a more practical and objective method to measure physical activity in clinical settings, epidemiological research, and behavior studies. Together with heart rate monitoring the development of motion sensors was an attempt to produce such an objective technique. The development of motion sensors, from mechanical devices up to more recently developed electronic accelerometers is reviewed here, after which the rationale and the reliability of the latter techniques will be dealt with.

Mechanical Motion Sensors

One of the earliest mechanical motion sensors is the pedometer, a stepcounter that consists of an arm balanced by a delicate spring. It is worn at the ankle or at the waist and in each step the impulse of the foot when landing will result in swinging of the balanced arm which through a series of gears is registered in a counting mechanism. The pedometer may be calibrated for stride length of the subject to convert steps into distance walked [1], [2]. Strictly speaking, the pedometer is not an accelerometer since it does not reflect the intensity of the movement. Hence, differences in energy expenditure are not accurately assessed [3]. Also the validity and reliability are rather poor [3]–[7].

The actometer, as proposed by Schulman and Reisman [8], is a modified wristwatch of which the escape mechanism has been removed, whereby any rotation of the rotor will be directly transduced to the hands. Activity can be interpreted from the resulting time displayed on the watch. This device reflects the amount and intensity of body movement and shows a fairly good correlation with energy expenditure in a variety of circumstances [3], [9], [10]. Despite a good reproducibility when used during standardized movements [3], [8], [11], [12] and a good test–retest reproducibility ($r = 0.67$) [13], the actometer shows a very large interinstrument variability which makes individual calibration essential [3], [10], [14].

Electronic Motion Sensors

The current generation of motion sensors is the electronic counterpart of the mechanical devices described above. Their evolution is the logical consequence of the development of integrated circuits during the last decade resulting in devices small enough to be socially acceptable. The first descriptions of electronic devices using the principle of measuring accelerations date from the early 1970's [15]–[18]. They were used to assess body movement in psychiatric patients [18], [19] or to assess the increase in physical activity coinciding with the estrus in cattle [20]. Based upon the type of sensor that is used two types of instruments can be recognized.

The first type is the large-scale integrated motor activity monitor (LSI) [19], [21], [22]. The sensor of the LSI consists of a cylinder with a ball of mercury. Inclination or declination of the sensor results in closing a switch by the mercury ball, which is registered in a counter. Montoye [23] reports test-retest coefficients of 0.44 to 0.98 for a mercury switch on the wrist and of 0.10 to 0.85 when the switch is worn on the waist in four subjects performing 14 standardized activities. Principle and accuracy of measurement of the LSI are comparable with those of the pedometer. The second type of electronic movement counters are real accelerometers. Although different types of sensors have been proposed [17], [18], [24]–[26] they all make use of the characteristics of piezoelectrical ceramics, the major property of which is that they evoke a charge when deformed in a special direction. The magnitude of the resulting voltage is directly related to the extension of the deformation. Deformation of the ceramic plate can be mechanically amplified by attaching a small mass to it [24], [26], or by the mass of the plate itself when it is clamped into a cantilever position [17], [18], [25]. Servais *et al.* showed that the instrument is valid in that

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it measures body acceleration very accurately compared to the output of a force platform [25]. Also high correlation coefficients (0.71–0.92) have been reported between accelerometer readings and energy expenditure measured by indirect calorimetry under different circumstances [24], [26], [27]. Unfortunately, until now, there is very little information available on the reliability of the technique. Nevertheless, it is obvious that, of all portable movement counters, the electronic accelerometers are the most promising ones due to their accuracy in measuring accelerations, the ease of calibration by gain adjustment, and the still growing possibilities of data storage on a single chip which will extend the length of time a subject can be studied as well as diminish the time resolution to shorter intervals.

A Rationale for Motion Sensor Techniques

Where the rationale for application of direct and indirect calorimetry lies in the laws of thermodynamics, the rationale for the use of accelerometers to measure physical activity lies in the mechanical laws of Newton. It can be stated that the goal one is aiming at when using an accelerometer is to assess movements of the body in order to get a quantitative measure of physical activity. Before outlining the rationale of movement counters for measuring physical activity we need a definition of physical activity in terms of body movement and its energetic consequences. It is clear that all physical activity is due to muscle contraction and will lead to energy output in heat loss and external work. This work may have dynamic properties, as in movement of the body, or static properties as in weight bearing. All body movements will have their concurring accelerations and decelerations. A large amount of empirical data shows a linear relationship between the integral of body acceleration and energy expenditure or oxygen uptake [28]–[31]. Therefore it seems reasonable that the measure of the integral of the absolute value of body acceleration serves as a good estimate of energy expenditure.

However it is too simple to state that physical activity is equivalent to movement [32], [33]. Neglecting the energy expenditure due to static work may have a large impact on the conclusions drawn from studies on physical activity, in particular when comparing subjects of different body mass [34], or when comparing subjects which may be expected to differ mainly in the amount of static work they perform [35]. The extra cost of weight bearing that occurs in the obese can be stressed by taking body weight in consideration when interpreting accelerometer readings in terms of energy expenditure, as is usually done by expressing the caloric equivalent of the accelerometer readings per kg body mass [23], [26]. However, static work due to lifting objects or climbing stairs cannot be expected to be accurately quantified by measuring body movement. One has to make the assumption that static work will only be of a small magnitude in the context of normal daily physical activity, and it should always be considered whether this assumption is valid for the population studied. Nevertheless, most researchers seem to agree on the validity of this assumption when suggesting that dynamic activities such as walking are the major contributors to physical activity in normal daily life [4], [6].

Site of Attachment

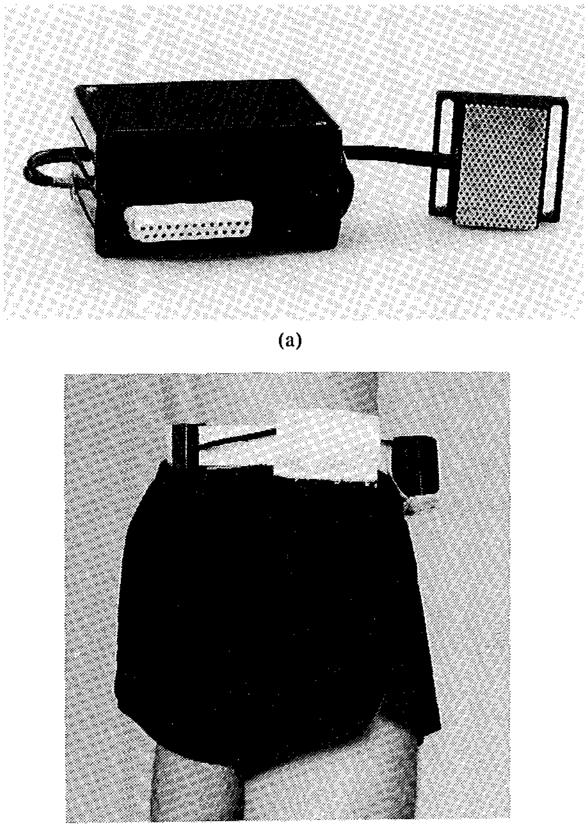
If one would like to assess all body accelerations due to muscular activity the subject would end up as a "christmas tree" full of accelerometers. In normal practice only one accelerometer is used, either attached to one of the limbs, or to the waist. The main question to be answered here is: where on the human body should the accelerometer be attached in order to obtain the most accurate estimate of energy expenditure? Tryon [12] refers to this as the "site of attachment issue." From a theoretical point of view, regarding the mechanical laws, it seems clear that the sensor should be attached to the trunk since this part of the body represents most of the body mass. It is for this reason that Cavagna *et al.* [36], [37] placed the accelerometer on the back, at the lumbosacral level as close as possible to the center of gravity of the body, when studying external work in walking and running. Nevertheless, one might argue that attachment to one of the limbs should be favored as this would more closely assess walking habits [4]. Although the swinging of the leg in walking and running will be clearly measured in this way, the attachment to the back seems superior, since: 1) it has been shown that body accelerations as a result of walking are very well detectable at this site [38]–[41], and can be measured with a high reproducibility [42] and 2) it is not necessary to choose between the dominant or the nondominant leg, considering the asymmetry of muscle forces that appear in normal human gait [43].

However, when attaching the accelerometer on the back or on the waist the assumption has to be made that the larger movements of the body (e.g., walking, running, jumping) have the greatest impact on daily activity level and that the influence of the smaller movements of the limbs (fidgeting) is negligible. Avons *et al.* [10] report on a complex technique using heart rate as well as three actometers, one at the wrist, one at the waist, and one on the leg. In five out of 12 subjects the wrist readings significantly improved the model of only one leg reading, compared with indirect calorimetry in a respiration chamber. Yet it is unclear whether these five subjects were fidgeting more than the others. Avons concludes that if one sensor should be used it certainly would have to be on the leg, but this conclusion is probably due to the fact that he used an actometer, an instrument which is most sensitive to rotation (swinging). In a study with children, Saris *et al.* [4] did not find a relation between actometer results from the wrist and daily physical activity based on observation score. This in contrast to the results obtained from ankle readings (actometer) or waist readings (pedometer).

METHODS

The Accelerometer Used in this Study

Previously, we described an accelerometer based upon a three directional sensor [26]. Data were stored using a portable tape recorder. Disadvantages were that tapes had to be changed every 24 h and that the size of the recorder was quite large which discouraged subjects from wearing it for more than a few days. In an attempt to challenge these problems we developed a new small data acquisition unit with a solid state memory [Fig. 1(a) and (b)]. The sensor is built in a plastic housing which has two wide slits by means of which is can be easily attached to a waist belt. The sensor weighs about 20 g and is connected to a small unit ($4 \times 6 \times 8$ cm/350 g) which carries the equipment for data acquisition and data storage as well as a rechargeable battery unit. A block diagram of the data acquisition unit is given in Fig. 2. The signal from the acceleration sensor first passes through a low pass filter of 30 Hz to attenuate signals with higher frequencies—which cannot be expected to arise from body movement—from further processing. After filtering, the signal is amplified, rectified, and integrated. Calibration of the instru-



(a)

(b)

Fig. 1. (a) The accelerometer used in this study. The picture shows the sensor connected to the data acquisition unit. (b) Subject wearing a belt carrying the accelerometer. The sensor is applied at the back.

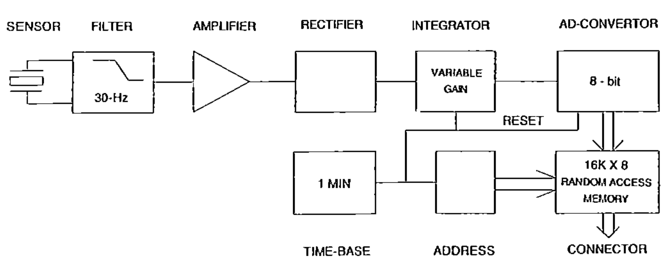


Fig. 2. Block diagram of the portable accelerometer with solid-state memory.

ment is possible through adjusting the gain of the integrator. A 1 min time pulse from the built-in timer triggers the conversion of the analogue value of the integral to an 8-bit value, which is stored in memory, after which the integrator is reset. Power consumption of the device is less than 1 mA. Recharging of the four nickel–cadmium cells is necessary only once every three weeks. However, batteries were recharged before every seven-day measurement period.

The sensor of this new accelerometer is exactly the same as the one previously described [26]. Shortly, a small mass is mounted on a square ceramic plate (1 cm^2) by means of a lever bent over two diagonally opposed corners. The other two corners are sustained by rubber feet. Due to this construction detection of accelerations in all three directions is enabled. The most important difference with the formerly used cassette recorder technique lies in the acquisition and storage of the data. Due to the 8-bit AD converter the maximum scaling of the data

TABLE I
DESIGN OF THE EXPERIMENT; NUMBER OF TRIALS WITH DIFFERENT COMBINATIONS OF SUBJECTS AND INSTRUMENTS

Device Set	*A*	*B*	*C*	*D*	*E*	*F*
Device No.	5 & 11	9 & 12	1 & 3	4 & 7	13 & 14	10 & 8
subject						
1	2	1	1			
2	2		1	1		
3	2			1	1	
4	2				1	1

is 256 counts/min. Since the integrator tends to have an offset of approximately 25 counts/min the effective range is from 0 to approximately 230 counts/min. The solid state memory consists of a 16 Kilobyte random access memory which enables monitoring during 11 days with a time resolution of 1 min. Afterwards data can be read out by means of a serial interface connected to the 25 p-i-n D-connector of the device and may be further processed on any personal computer system.

Experimental Design

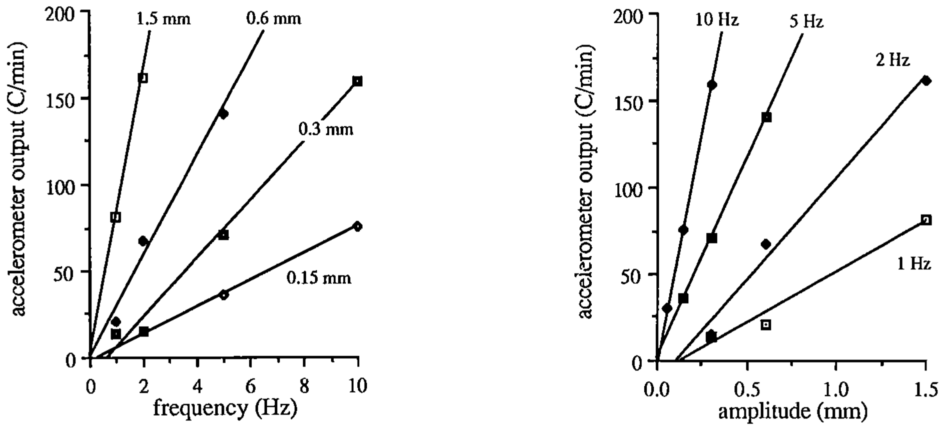
In order to cover questions concerning the reproducibility of the instrument as well as concerning the interinstrument and interindividual variation, a Latin square type of protocol was designed in which four healthy subjects (two males, two females; age 22 ± 1 year, length 179 ± 6 cm, weight 66 ± 9 kg) walked on a treadmill at three different speeds (3, 5, and 7 km/h) for five min at each speed (Table I). The 12 different accelerometers used in this study were divided in six sets (sets *A* to *F*). During all sessions the subjects wore one set of two accelerometers, the sensors of which were placed closely together on the same waist belt at the lower part of the back. The sessions with set *A* were repeated in a second trial one week after the first trial to study the reproducibility in time.

Bench Test

All devices were tested in a standardized way (bench test). A speaker connected to a frequency oscillator with variable amplitude settings was used to produce up and down movements. The accelerometer shows a linear response both to frequency and amplitude of the movement [Fig. 3(a) and (b)]. Therefore one frequency and amplitude setting may serve for calibration purposes. The response to a movement with a frequency of 5 Hz and an amplitude of 0.6 mm was chosen, as these values lie close to those which may be expected on the lower part of the back [41], [44]; they result in an output of approximately 75% of the maximum output of the device. Correction factors were calculated converting the output of the accelerometer to 150 counts/min.

One day before and after the treadmill sessions the accelerometers were calibrated using this bench test. Thus four trials were conducted, two trials within 48 h being repeated after one week. Analysis of the treadmill sessions were conducted both on the uncorrected data and the corrected data to study the effectiveness of these corrections.

To study the accuracy and reproducibility of the instrument, percentage differences between first and second trail were calculated for each different speed, individual, and instrument. Also an analysis of variance (Anova) was conducted on the data of set *A* to reveal interindividual differences.



(a) (b)

Fig. 3. (a) Response of the accelerometer to different frequencies at fixed amplitudes. (b) Response of the accelerometer to different amplitudes at fixed frequencies.

TABLE II
RESPONSE OF TEN ACCELEROMETERS DURING THE BENCH TEST. MEAN, SD, AND CV ARE CALCULATED OVER FOUR TRIALS

Device No.	Trial		Difference		Trial		Difference		Mean (cpm)	SD (cpm)	CV %
	1 (cpm)	2 (cpm)	(cpm)	%	3 (cpm)	4 (cpm)	(cpm)	%			
1	55	56	1	1.8	65	57	−8	−13.1	58.3	4.6	7.9
3	177	161	−16	−9.5	159	155	−4	−2.6	163.0	9.7	5.9
5	144	154	10	6.7	127	133	6	−4.6	139.5	12.0	8.6
8	155	142	−13	−8.8	134	123	−11	−8.6	138.5	13.5	9.7
9	164	158	−6	−3.7	152	132	−20	−14.1	151.5	13.9	9.2
10	159	158	−1	−0.6	146	138	−8	−5.6	150.3	10.1	6.7
11	139	135	−4	−2.9	123	115	−8	−6.7	128.0	11.0	8.6
12	139	152	13	8.9	146	141	−5	−3.5	144.5	5.8	4.0
13	157	167	10	6.2	149	133	−16	−11.4	151.5	14.4	9.5
14	146	148	2	1.4	135	130	−5	−3.8	139.8	8.7	6.2
mean	143.5	143.1	−0.4	−0.1	133.6	125.7	−7.9	−6.5			7.6
SD	33.3	32.0	9.7	6.3	26.7	26.4	7.1	5.6			1.9

(cpm) = count/min
Time between trial 1 and 2 and between trial 3 and 4 was 48 h; the interval between trials 1/2 and the trials 3/4 was one week.

The coefficient of variation (CV) of the 1 min readings during each 5 min of exercise was calculated as a measure of within measurement reproducibility.

RESULTS

Bench Test

The results of set *D* (devices no. 4 and 7) were excluded from analysis. Device no. 7 was excluded because it had a response of only 10% compared to the other instruments. The response of device no. 4 decreased over 30% during the week of measurement indicating malfunctioning of the sensor unit. Within 48 h response to the bench test shows a mean percentage difference for all instruments of −0.1 and −6.5% in the first and second week respectively. The mean CV over 4 trials is 7.6% (Table II). All instruments had CV's less than 10%; most of them came close to the ideal response of 150 counts/min as a consequence of which correction factors were small.

The mean response of the instruments decreased from 143.5 counts/min during the first trial to 125.7 counts/min during the last trial. This decrease is due to the properties of piezo-electric ceramics, and will be discussed in greater detail later on in this paper.

TABLE III
AVERAGE OF 22 OBSERVATIONS (ALL SUBJECTS, ALL ACCELEROMETERS) OF MEAN ACCELEROMETER OUTPUT (AO), STANDARD DEVIATION AND COEFFICIENT OF VARIATION AT DIFFERENT WALKING SPEEDS

	Walking Speed (km/h)		
	3	5	7
mean AO (cpm)	26.5	62.8	128.2
range	13.8–36.8	29.4–86.3	63.3–182.0
mean SD (cpm)	1.1	1.5	2.2
range	0.5–3.3	0.0–6.6	0.8–5.0
mean CV (%)	4.1	2.5	1.8
range	1.6–9.9	0.0–8.3	0.7–3.8

cpm = counts/min

Treadmill Experiment

Within the 5 min exercise periods accelerometer output showed little variance. The SD averaged over 22 observations was between 1 and 2.2 counts/min (Table III). In the individual cases the SD of accelerometer output never exceeded 7

TABLE IV
TEST–RETEST RESULTS OF ACCELEROMETERS 5 AND 11 OBTAINED IN TREADMILL EXPERIMENTS IN FOUR SUBJECTS WITH AN INTERVAL OF ONE WEEK

	Device No. 5					Device No. 11			
	Experiment		Difference			Experiment		Difference	
	1 (cpm)	2 (cpm)	(cpm)	%		1 (cpm)	2 (cpm)	(cpm)	%
					3 km/h				
mean	37.3	29.6	−7.7	−21.3		23.8	27.1	3.3	13.5
SD	9.1	3.4	8.0	21.5		5.0	4.5	7.1	26.6
CV	24.3	11.6				21.0	16.7		
range (min)	28.4	26.0	−15.3	−42.4		18.5	24.3	−6.2	−22.6
(max)	48.8	33.5	−0.7	−2.2		30.5	33.8	10.6	37.2
					5 km/h				
mean	80.1	76.8	−3.2	−3.0		56.0	64.8	8.8	14.2
SD	15.8	8.4	14.7	17.5		7.7	11.0	8.7	13.5
CV	19.7	10.9				13.8	16.9		
range (min)	61.4	66.0	−23.2	−26.5		49.0	52.3	0.0	0.0
(max)	99.0	86.0	10.5	13.0		63.5	79.0	17.2	27.0
					7km/h				
mean	169.9	154.5	−15.4	−8.8		130.6	134.2	3.7	3.0
SD	36.0	26.0	15.0	7.6		29.0	27.6	3.9	2.8
CV	21.2	16.9				22.2	20.6		
range (min)	127.3	124.0	−37.3	−19.9		103.3	107.8	−1.9	−1.2
(max)	206.3	182.0	−3.3	−2.6		158.7	159.6	7.0	4.5

(cpm) = count/min

counts/min. The mean coefficient of variation is less then 5% and decreases with increasing walking speed.

The results show that the output of the accelerometer reflects walking speed in an exponential way.

Table IV presents the test–retest data of the treadmill experiment for the four subjects and the two devices of set *A*. It appears that the mean percentage difference between first and second trail is about 20% at the speed of 3 km/h and is less than 10% at the speed of 7 km/h. Differences between subjects as interpreted from the CV over subjects is only slightly larger than the error of repeated measurement. Nevertheless a three factor repeated measure Anova revealed that significant differences could be found between walking speed (F 124.0, $p < 0.0001$) and subjects (F 4.6, $p < 0.05$), whereas the repeated measure showed no significant difference (F 0.46, $p > 0.5$).

Correction factors calculated from Table II are 1.01 and 1.15 for device no. 5 and 1.09 and 1.26 for device no. 11 for the first and second experiment, respectively. Applying these correction factors to the data did not improve the reproducibility, although subjects were better discriminated in the Anova (F 11.0, $p < 0.001$).

Neglecting the rather poor result at 3 km/h— since this walking speed is of little relevance in normal daily life—it can be concluded that the reproducibility of the accelerometer is within 18%. This would imply a correlation coefficient of $r = 0.91$. The regression coefficient between the results of trial 2 versus trial 1 (Table IV) is 0.98. The standard error of estimate is 11.2 counts being about 14% of the mean (X, Y) (Fig. 4).

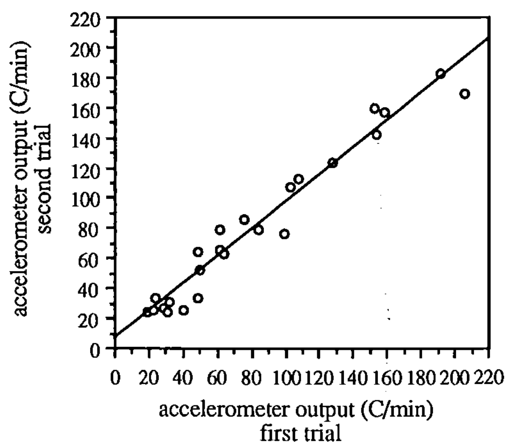


Fig. 4. Scattergram of the accelerometer output from trial 2 versus trial 1 of the test–retest experiment on the treadmill ($n = 24$, $r = 0.98$, $S_{y,x} = 11.2$, $p < 0.001$).

Interinstrument Variation

The interinstrument variation has been studied looking at the output of two instruments worn together under similar circumstances. Table V shows the results of this comparison between instruments x and y within sets *A–F* (see Table I). The percentage difference between two instruments usually is less then 30%. The difference in set *C* is much higher (due to the low response of device no. 1) and exceeded mean ±2 times SD for all sets. Therefore, set *C* was excluded from this analysis. The SD of the percentage difference is approximately 22% independently of walking speed. Appliance of the correction factors based upon differences in the bench test did not decrease interinstrument variation.

Variation in Response of Accelerometers in Time

The decline in response to the mechanical calibration after one week, which was found in almost all instruments, led us to reanalyze all calibration data collected during the last year. It was known that the response of a particular instrument could vary largely, although no explanation for this effect could be

TABLE V
DIFFERENCES BETWEEN OUTPUT OF ACCELEROMETERS x AND y OF SETS A–F (SEE TABLE I) WHEN WORN AT THE SAME TIME AND UNDER SIMILAR CIRCUMSTANCES (n = 9[1])

	Data					Corrected Data[2]			
	Device		Difference			Device		Difference	
	x (cpm)	y (cpm)	$x - y$ (cpm)	$x - y$ %		x (cpm)	y (cpm)	$x - y$ (cpm)	$x - y$ %
					3 km/h				
mean	28.0	26.6	1.4	5.9		28.9	29.5	−0.6	−1.2
SD	3.9	5.4	6.3	22.8		4.7	6.2	6.8	22.4
range (min)	19.6	19.0	−7.8	−26.1		19.4	20.5	−11.5	−33.9
(max)	33.5	33.8	−10.8	44.3		36.2	39.5	9.3	36.9
					5 km/h				
mean	68.6	64.3	4.4	7.0		71.1	71.3	−0.2	−0.1
SD	11.0	12.5	14.8	21.4		13.9	14.6	15.7	21.2
range (min)	52.0	50.8	−23.9	−32.1		51.5	52.8	−30.6	−39.7
(max)	86.0	86.3	21.7	32.0		85.9	92.4	17.6	24.5
					7km/h				
mean	135.3	130.7	4.6	3.4		140.3	146.3	−4.9	−3.7
SD	27.2	25.8	28.4	22.0		33.0	32.6	29.4	21.7
range (min)	92.5	97.0	−52.5	−37.9		91.6	104.8	−65.2	−45.3
(max)	182.0	164.8	31.8	28.2		196.6	186.4	24.0	20.6

[1]Data of set C were excluded from calculation of mean and SD at all speeds since they lied outside the range: mean ± 2 times SD at 3 and 5 km/h.
[2]Corrected for differences in the bench test calibration (see text).

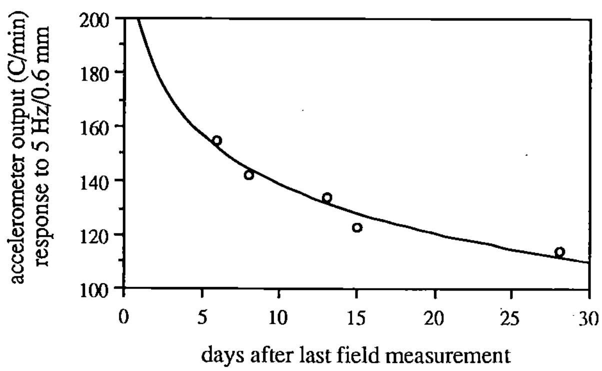


Fig. 5. Logarithmic decline of sensitivity of the piezoelectric sensor not used for a longer time ($y = 199 - 60.4 \log (x)$; $r^2 = 0.951$).

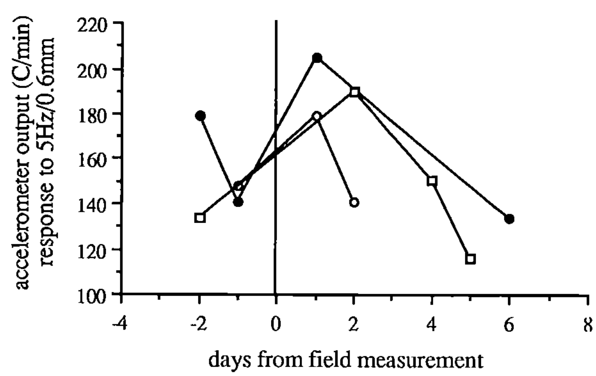


Fig. 6. Three observations of the sensitivity of an accelerometer plotted against the day before or after a seven-day field measurement period (vertical line). Note the increase of response after outdoor measurement and subsequent decrease when the accelerometer is not used.

found. Most instruments were very frequently used in field measurements, and calibrated during the short periods they were in the laboratory. At the time of the treadmill test–retest experiments, however, they were all in the laboratory and had not been used for two weeks.

To see whether the decreasing trend in response which appears in Table II extends over a longer period of time, all calibration data per instrument were plotted against the number of days after the last field experiment. These plots revealed a decline in response in all instruments which usually appeared to be logarithmic. A typical example is shown in Fig. 5. The rate of loss of sensitivity averaged about 15% in the first week.

Secondly all calibration points of each particular device were plotted against time before or after a field measurement period (Fig. 6). Of 28 observations where a calibration point was collected both one day before and one day after a field experiment of one week, 23 showed an increase and five a decrease in sensitivity (Table VI).

TABLE VI
DIFFERENCE IN RESPONSE OF ACCELEROMETERS TO THE BENCH TEST ONE DAY BEFORE ($d - 1$) AND ONE DAY AFTER ($d + 1$) A SEVEN-DAY FIELD EXPERIMENT (n = 28)

	$d - 1$ (cpm)	$d + 1$ (cpm)	Difference (cpm)	Difference %
mean	133.2	164.5	30.6	23.8
SD	26.9	42.3	31.9	26.3
range (min)	63.0	70.0	−37.0	−34.7
(max)	171	213	93.0	83.0

DISCUSSION

With respect to the evaluation of different motion sensors for the measurement of human physical activity all authors agree that the recently described accelerometers based on a piezoelectric sensor look most promising [23], [26], [45], [46]. However, until now very little validation studies have been published. Even less material is available on the reliability of these devices. Only Montoye [23] claims a very good reliability based on a correlation of 0.94 between first and second trial in a test–retest situation. In our test–retest experiment we found a correlation of 0.98 between both trails. However, a more detailed study on the percentage differences shows that there is quite a large error of up to 20%. It is evident that just plotting all activities of trial one versus trial two is not concerned per se with the reproducibility. Activities that were discriminated as being high in the first trial also appear to be high in the second trial. However, the absolute outcome in the second trial may differ strongly. Montoye does not present the actual values of his measurements but the scattergram, with different scaling on the X- and Y-axis, suggests that the mean percentage difference is also about 20%, whereas individual measurement may differ over 100%.

Tryon [12] and Saris [45] argue that the accuracy of motion sensors should be based on data from standardized mechanical movements, because of the irreproducibility of human movement itself. The reproducibility of the accelerometer is indeed better when looking at the response to a standardized mechanical movement; the CV over four trials in one week is less than 10%. Intrainstrument reproducibility in the test–retest experiment is within 20%, whereas interinstrument variation is about the same. Despite this quite large error, differences between subjects performing the same activities could be discriminated significantly using an Anova ($p < 0.05$). It appears that the sensitivity of a piezoelectric sensor may vary largely over time. The logarithmic decrease in sensitivity when the sensor is not used for a longer period is generally known and described as aging of the ceramic [47]. The rate of loss of sensitivity of 15% in the first week we found in this study indicates that our sensors had a good time stability. In general this means that a few weeks after manufacturing the sensitivity will only fall with a very small percentage. Aging occurs as a result of partial depolarization of the ceramic and inactivation of some of the dipoles in the material. However, both processes are reversible. Sensitivity may be increased again as a result of a mechanical, electromagnetic, or temperature shock. Apart from these effects the sensitivity of the element may vary with temperature and humidity. Although we do not know which of these different factors are responsible for the increase in sensitivity of our sensors after a field measurement of one week, it is clear that they all may occur under these circumstances.

Despite this finding of changing sensitivity to a standardized mechanical test, the corrections we made for these changes did not improve intra- and interinstrument reproducibility in the test–retest experiments. Since this standardized movement lies reasonably close to normal human movements that may be expected at the lower part of the back, it can only be concluded that still other factors influence the output of the accelerometer at similar activities. For the intrainstrument reproducibility it may be questioned whether the actual movement of a subject during a standardized activity is reproducible within 20% over a week. Furthermore, the precise attachment site and the tightness of the sensor to the body may be of influence, although this was reasonably under control using a standardized waist belt which ensured the sensor to be firmly bound to the body.

Evaluation of the results of this study with earlier validation studies on motion sensors is quite complex because of the different methods used. For instance, Tryon reports very high reproducibility of the actometer on a standard mechanical movement. However, actometer response was tested in ten trials within 2 h and without even removing the actometer from the pendulum [12]. More recently, Morell reported very poor reproducibility of the actometer in a test–retest experiment on three consecutive days, the percentage difference being 45% in subjects walking three laps of respectively 32, 128, and 224 yards [48]. Since motion sensors are intended to be used over longer periods of several days or even a week, in our opinion reproducibility should at least be studied on a comparable time scale. In this respect an accelerometer based on a piezoelectric sensor seems to be superior to other motion sensors. To improve these devices, the changes in sensitivity we found need further attention, although the relevance of the bench test in this study may be questioned, as results did not correspond with findings in subjects.

Concluding from our data the accelerometer is accurate within 18% when used under standardized conditions in the laboratory. In order to assess the accuracy of this technique when used on subjects going through their normal daily activities a validation versus the doubly labeled water technique seems the ultimate approach.

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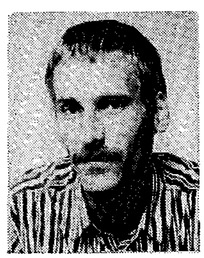

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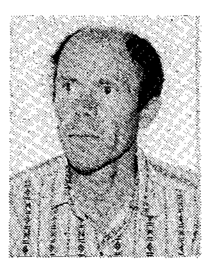

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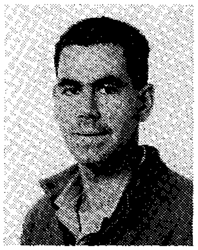

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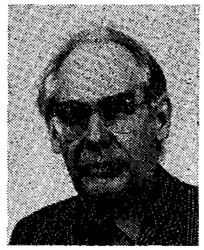

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