

VALIDITY OF AMBULATORY ACCELEROMETRY TO QUANTIFY PHYSICAL ACTIVITY IN HEART FAILURE

Hendrika J. G. van den Berg-Emons,¹ Johannes B. J. Bussmann,¹ Aggie H. M. M. Balk² and Henk J. Stam¹

From the ¹Department of Rehabilitation Medicine, Erasmus University Rotterdam, Rotterdam, The Netherlands, ²Thoraxcenter, University Hospital Rotterdam-Dijkzigt, Rotterdam, The Netherlands

The purpose was to assess the validity of a novel Activity Monitor to quantify physical activity in congestive heart failure. The Activity Monitor is based on long-term ambulatory monitoring of signals from body-fixed accelerometers. Information can be obtained on which mobility-related activity is performed, when, how intense, and for how long. Ten patients performed several functional activities. Continuous registrations of accelerometer signals were made and the output was compared with visual analysis of simultaneously made video recordings (reference method). Overall results showed an agreement between both methods of 90%. Percentages of sensitivity and predictive value were higher than 80% for most activities. Overall number of transitions was determined well (Activity Monitor, 153; video, 149; $p = 0.33$). It was concluded that the Activity Monitor is a valid instrument to quantify several aspects of everyday physical activity in congestive heart failure.

Key words: activity monitor, accelerometry, activity detection, heart failure.

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Correspondence address: Rita J. van den Berg-Emons, Department of Rehabilitation Medicine, University Hospital Rotterdam-Dijkzigt, P.O. Box 2040, 3000 CA Rotterdam, The Netherlands
E-mail: vandenber@revd.azr.nl

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INTRODUCTION

Due to dyspnea and fatigue, patients with congestive heart failure (CHF) are restricted in the performance of daily activities such as walking, house-keeping and gardening (1–4). Measurement of everyday physical activity is important in this population because it provides valuable information on disability in daily functioning and the prognosis of the patient (5). Furthermore, it can be assumed that everyday physical activity is related to quality of life.

Commonly used methods in the CHF population are exercise tolerance tests (6–8) and the New York Heart Association (NYHA) functional classification (9). However, these methods have been found to be inadequate in predicting the actual everyday physical activity (2, 5, 10). Until now, a few studies

are available on the intensity (or level) of everyday physical activity in CHF. Techniques that have been used in these studies include an actometer (2, 10), pedometer (5, 11, 12), calorimeter (13), and the doubly labelled water technique (14, 15).

In our department, an Activity Monitor (AM) has been developed, by which detailed information can be obtained on several aspects of everyday physical activity (16, 17). Briefly, the AM is based on long-term (more than 24 h) ambulatory monitoring of signals from body-fixed accelerometers. From these signals, the duration, rate and moment of occurrence of body postures (lying, sitting and standing), dynamic activities (walking, walking stairs, cycling, wheelchair driving, general movement), and transitions between postures can be detected. Information on the intensity of activities (motility, is related to speed (18, 19)) can also be obtained from the device. Apart from monitoring accelerations, other signals can be measured simultaneously, such as heart rate or ECG.

The AM may be of extra value for research or clinical practice in CHF, because it provides detailed information on several aspects of everyday physical activity. This is in contrast to existing methods (actometry, pedometry, calorimetry), by which no specification of the activities performed can be given. Particularly, the AM outcome measures number and duration of walking periods and resting (lying, sitting) periods, walking speed, and the distribution of activities over the day, are clinically relevant in the treatment of CHF.

The AM has been found to be valid in healthy subjects, patients after failed surgery of the back, and patients with an amputation of the leg (20–22). However, patients with CHF may differ from the above-described study groups (20–22) on specific mobility-related aspects, which may result in decreased validity of the AM in this patient group. Firstly, patients with CHF perform movements (very) slowly. This may, for example, lead to an underestimation of the duration of walking by the AM, in favour of the duration of standing or general movement. Secondly, patients with CHF often lie in bed with two or more pillows, which may be (falsely) detected by the AM as sitting. The ability to distinguish between lying and sitting is important in CHF, because shifts within this resting category may reflect changes in the condition of the patient.

Preceding a large intervention study on the effects of aerobic training on daily physical activity in patients with mild to moderate CHF, the aim of the present study was to assess the

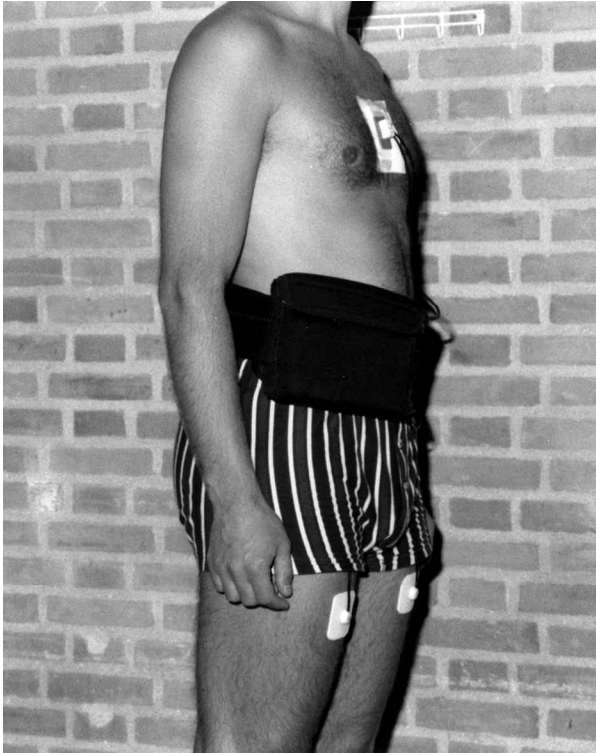


Fig. 1. Subject wearing the Activity Monitor (Vitaport2[™]).

validity of the AM to quantify physical activity in patients with CHF (NYHA class II and III). Furthermore, the practical feasibility of measurements with the AM in this population was studied.

MATERIALS AND METHODS

Study group

Ten patients (9 men; 1 woman) with stable CHF were recruited from patient records of the Thoraxcenter of the University Hospital Rotterdam. Informed consent was obtained from all patients. Five patients were in NYHA class II, four in class III, and one patient was borderline III/IV. All patients had symptoms of CHF for at least 1 year. Their age ranged from 34 to 72 years (median 63 years). Left ventricular ejection fraction ranged from 19 to 36% (median 26%). The study was approved by the Medical Ethics Committee of the University Hospital Rotterdam.

Activity Monitor (see Fig. 1)

Four IC-3031 uniaxial piezo-resistive accelerometers were used (supplied by Temec Instruments BV, Kerkrade, The Netherlands; size $2 \times 2 \times 0.5$ cm). The measured acceleration signal contains a component of the gravitational acceleration and of the actual acceleration of the sensor. One sensor was attached to the skin of each leg at the front of the thigh (approximately halfway between spina iliaca anterior superior and the top of the patella; while standing the sensor is sensitive in the anterior-posterior direction). The other two sensors were attached to the skin over the sternum, perpendicular to each other (while standing one sensor is sensitive in the anterior-posterior direction and one in the longitudinal direction). The sensors are attached in such a way that, while the subject is standing, their axes are as close as possible to the vertical or horizontal plane (deviation $< 15^\circ$). The sensors were fixed

onto the skin using Rolian Kusionflex; adhesive medical tape was used to strengthen the attachment.

The accelerometers were connected to a Vitaport2[™] data recorder (Temec Instruments BV; size $15 \times 9 \times 4.5$ cm; weight 700 g), which was worn in a padded bag around the waist. Signals were digitally stored on a PCMCIA hard disk, with a sampling frequency of 32 Hz. After the measurement, the data were analysed (Macintosh computer) by means of the Vitagraph[™] and Signal Processing and Inferencing Language (S.P.I.L.[™]) (23). A detailed description of the activity detection procedure can be found elsewhere (17). Briefly, from each measured signal, three feature signals are derived: an angular feature signal, a motility feature signal, and a frequency feature signal. For consecutive moments in time (1 second), the distance of the feature signals to ranges that are pre-set for several activities in an activity detection knowledge base is calculated. The calculated distances of the feature signals are added for each activity and the activity with the shortest distance is selected. The following activities were distinguished: (a) body postures lying (on the back, on the side, prone), sitting and standing; and (b) dynamic activities walking, walking stairs, cycling, wheelchair driving, and general movement (unspecified non-cyclic movements). Short activities (< 5 seconds) were disregarded by the analysis program. The output of the AM—the continuous selection of an activity—had a time resolution of 1 second. Fig. 2 shows an example of the accelerometer signals during subsequent activities, the output of the AM and video, and the motility feature.

Protocol and reference method

In order to obtain information on the validity of the AM during natural activities, measurements with the AM were performed in and around the patients' homes. After explaining the protocol, patients were asked to perform several representative everyday activities in their own way and at their own pace. Activities were passive (e.g., sleeping), semi-passive (e.g., watching television, reading), semi-active (e.g., standing, writing a letter, playing cards, peeling potatoes, driving a car), or active (e.g., dressing, washing dishes, walking (stairs), cycling). The activities were selected by a cardiologist. Patients only performed the activities which they were used to do. Duration of activities varied from 2 to 4 minutes per activity; total measurement time was about 45 minutes per patient.

Simultaneously to the performance of activities, video recordings were made (also outside while cycling and while car-driving), and these were used as the gold standard. All video recordings (time resolution is 1 second) were made and analysed by the same person (inter-rater agreement was studied in a previous study (21) and was found to be 99.7%). Video recordings were synchronized with the accelerometer recordings by taps on the sensors. Inadequate video recordings were excluded from analysis. The analysed video recordings were transferred to a signal in the AM file; all calculations and comparisons were automatically performed by means of the S.P.I.L.[™] software (23).

Data analysis

The continuous output of the AM was compared with the synchronized, continuous output of the video analysis. The following agreement scores were calculated:

1. *Agreement*: (number of identical samples of the video and AM/total number of samples) $\times 100\%$.
2. *Sensitivity for each video activity category*: (number of identical samples of the video and AM for a video activity category/total number of samples for this video activity category) $\times 100\%$.
3. *Predictive value of each AM activity category*: (number of identical samples of the video and AM for an AM activity category/total number of samples for this AM activity category) $\times 100\%$.

When the number of the AM or video samples of a specific activity category was less than 20 (one sample equals 1 second), sensitivity and predictive value were not calculated. Finally, the duration of activities, the number of walking periods (> 10 seconds), and the number of transitions were calculated and a comparison was made between the video and AM using the Wilcoxon matched-pairs signed-ranks test. All statistics were done using SPSS/PC⁺, statistical significance was assumed when $p < 0.05$.

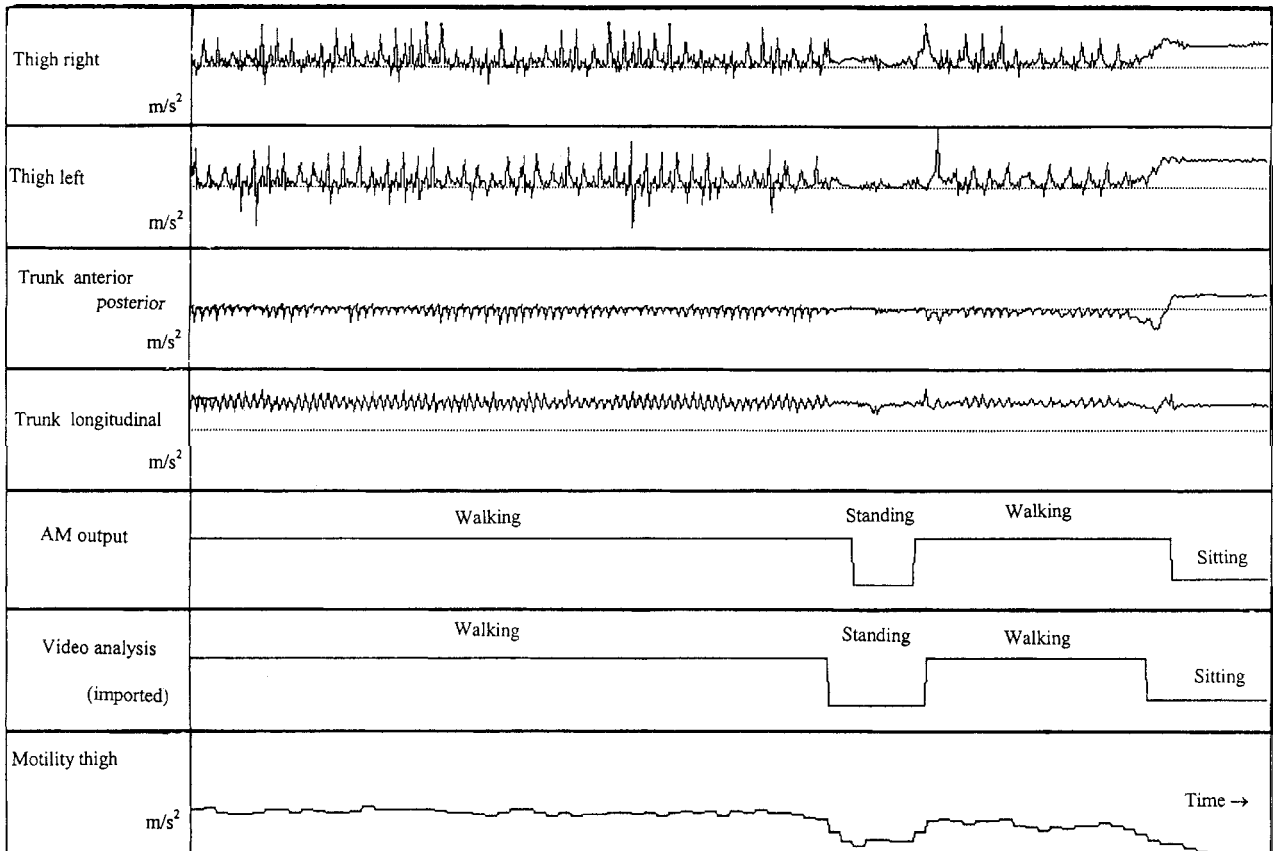


Fig. 2. Example of the four raw accelerometer signals (two leg sensors, two on the trunk) and the output of the Activity Monitor (AM). This 90-second part shows a sequence of activities as indicated by the output of the AM; the lower curves present the imported video signal and the corresponding motility signal of the legs (AM) respectively.

RESULTS

Practical feasibility

Some patients experienced the AM as being rather heavy (particularly in view of long-term measurements), whereas the device was of no hindrance to others. However, the devices we plan to use for long-term (> 24 h) measurements, are lighter (500 g) and smaller (15 × 9 × 3.5 cm) than the AM described. Apart from one patient with severe skin problems, all patients well tolerated the materials used for the attachment of the sensors.

Agreement measures

In Table I the number of corresponding and non-corresponding counts of the video and AM are presented.

The mean overall agreement between video analysis and AM output was 90% (ranging from 82 to 97%, Table II). The overall sensitivity was higher than 80% for lying, standing, sitting, walking and cycling (Table II). The overall predictive value was higher than 80% for lying on the side, standing, sitting, walking (stairs) and cycling. The extremely low sensitivity for walking (13%) in subject 5 (borderline class III/IV) is remarkable.

Duration of activities and number of walking periods and transitions

The overall duration of the dynamic activities (as a percentage of the measurement time) tended to be overestimated by the AM (16.6% by AM versus 14.4% by video analysis), but the difference was not statistically significant ($p = 0.14$). Table III shows the duration of the activities per measurement. The AM overestimated the durations of lying on the back ($p = 0.04$) and general movement ($p = 0.02$). The duration of sitting and walking stairs was underestimated by the AM ($p = 0.005$ and $p = 0.03$, respectively).

The number of walking periods tended to be overestimated by the AM (video 94, AM 110), but the difference was not statistically significant ($p = 0.08$). The total number of transitions did not differ between the video and AM (video, 149; AM, 153; $p = 0.33$).

DISCUSSION

In the present study, an overall agreement of 90% was found between the AM output and video analysis. This result is comparable with the agreement scores found in previous validation studies of the AM (87–90%) (20–22). Recently, a

Table I. Number of corresponding and non-corresponding counts (one count = 1 second) of video (rows) and Activity Monitor (AM, columns), added for all measurements

Video ▼	AM ►	Lying on back	Lying on side	Standing	Sitting	General movement	Walking	Walking stairs	Wheel chair driving	Cycling	Total
Lying on back		2185*	13	2	0	7	7	0	0	6	2220
Lying on side		82	2605*	0	8	26	4	0	0	0	2725
Standing		2	0	4608*	46	89	396	0	0	0	5141
Sitting		791	11	17	10735*	97	105	0	272	9	12037
General movement		26	8	10	5	22*	6	0	0	10	87
Walking		7	0	350	43	46	2836*	0	0	0	3282
Walking stairs		0	0	2	0	5	65	70*	0	0	142
Wheelchair driving		0	0	0	0	0	0	0	0*	0	0
Cycling		0	0	0	5	0	2	0	0	202*	209
Total		3093	2637	4989	10842	292	3421	70	272	227	25843

*Corresponding counts.

study with the AM in patients with CHF and healthy control subjects (17) has shown that the AM is able to detect differences in everyday physical activity between groups, which supports its validity and usefulness for clinical research.

One of the motives for this study was concern regarding the effect of slow movements on the validity of the AM in patients with CHF. The results of the study indicate that this concern was only justified for the detection of walking in one severely affected patient (borderline class III/IV), who walked extremely slowly (sensitivity for walking was only 13%, Table II). Due to extremely low motility of the trunk and legs and no detected frequency of the trunk, walking in this patient was mainly detected as standing. This finding implies that the pre-set ranges of motility and frequency for walking in the activity detection knowledge base may have to be adapted when using the device in severely affected CHF patients. This is no problem, because

the structure of the analysis program allows for user-specific or measurement-specific settings.

Walking stairs was relatively often detected by the AM as walking (reverse misdetection did not occur, Table I), which resulted in an overall sensitivity for walking stairs of 49% (Table II). However, this is not specific for the CHF population: comparable percentages of sensitivity were found in other populations (17). Future research in our department will focus on optimizing the detection of walking stairs.

The low predictive value and sensitivity percentage of the activity category general movement (Table II) should not receive too much attention because this output category was not exactly comparable between the analysis techniques: the AM category general movement contains all non-cyclic movements with a considerable degree of motility, whereas the video category contains only transitions. In only two patients was

Table II. Percentages per measurement, representing the sensitivity (S), predictive value (PV) and agreement

Subject	Sensitivity and predictive value (%)																Agreement (%)
	Lying on back		Lying on side		Standing		Sitting		General movement		Walking		Walking stairs		Cycling		
	S	PV	S	PV	S	PV	S	PV	S	PV	S	PV	S	PV	S	PV	
1	99	99	100	98	93	95	94	98	22	29	89	82	24	-	-	-	93
2	100	93	100	99	92	90	99	99	35	70	82	84	-	-	-	-	95
3	94	96	98	97	87	97	98	99	-	0	86	69	30	-	-	-	93
4	98	39	99	98	93	92	80	99	0	0	83	88	81	-	-	-	86
5	98	94	98	99	95	66	98	97	13	0	13	82	-	-	-	-	92
6	99	77	77	100	82	92	89	100	-	0	91	82	43	-	98	100	87
7	99	99	99	100	98	97	97	99	0	0	92	94	-	-	-	-	97
8	97	98	99	99	86	92	89	100	-	0	93	82	39	-	-	-	90
9	-	0	99	100	93	88	89	99	52	44	84	89	-	-	-	-	90
10	99	63	94	98	83	98	68	98	0	0	96	80	83	100	96	85	82
Weighted overall mean	98	71	96	99	90	92	89	99	25	8	86	83	49	100	97	89	90

- The activity is not performed or detected, or is less than 20 seconds.

Table III. Duration per measurement (as percentage of the measurement time) of each category, determined by the Activity Monitor (AM) and video analysis (V)

Subject	Duration															
	Lying on back		Lying on side		Standing		Sitting		General Movement		Walking		Walking stairs		Cycling	
	V	AM	V	AM	V	AM	V	AM	V	AM	V	AM	V	AM	V	AM
1	17.2	17.2	5.3	5.4	27.1	26.4	36.3	34.8	0.4	0.3	12.7	13.8	0.9	0.2	–	–
2	5.0	5.4	9.1	9.2	21.2	21.7	53.0	52.6	0.8	0.4	11.0	10.7	–	–	–	–
3	6.3	6.2	15.6	15.8	28.8	25.9	37.7	37.2	0.0	1.9	10.3	12.7	1.3	0.4	–	–
4	6.4	16.3	9.2	9.3	19.6	19.7	52.7	42.9	0.2	0.7	11.0	10.4	0.8	0.6	–	–
5	13.3	14.0	23.0	22.9	12.2	15.3	45.1	44.9	0.8	2.0	5.5	0.9	–	–	–	–
6	8.2	10.6	12.9	10.0	18.8	16.7	40.9	36.5	0.0	1.9	16.4	18.3	0.8	0.3	2.1	2.1
7	6.6	6.6	9.1	9.0	22.0	22.1	50.1	49.4	0.2	1.1	12.0	11.7	–	–	–	–
8	4.5	4.4	12.4	12.3	16.7	15.6	48.3	42.9	0.0	1.0	17.3	19.7	0.8	0.3	–	–
9	0.0	5.6	8.7	8.6	17.4	18.4	58.4	52.4	0.7	0.9	14.8	14.0	–	–	–	–
10	19.1	30.0	4.0	3.9	17.3	14.6	41.5	28.9	0.3	1.3	12.6	15.1	0.8	0.6	4.5	5.1
Weighted overall mean	8.6	12.0*	10.5	10.2	19.9	19.3	46.6	42.0\$	0.3	1.1†	12.7	13.2	0.5	0.3‡	0.8	0.9

* $p = 0.04$, \$ $p = 0.005$, † $p = 0.02$, ‡ $p = 0.03$, video versus AM.

cycling included in the protocol. However, the agreement scores found in these patients suggest that cycling is well detected by the AM in CHF patients.

Our second concern was the misinterpretation by the AM of lying as sitting. Three patients in our study slept in a more upright position (according to the video analysis this was lying), but in none of them was lying (falsely) interpreted by the AM as sitting. Therefore, our concern was not justified. On the other hand, sitting was, in 791 seconds (7% of the time during sitting) (Table I), detected as lying on the back. This misdetection occurred during sitting in a slouching position and during reading in bed while the headend had been put in a more upright position, and can be explained by a small difference in frame of reference between the video analysis and AM. The criteria of the video analysis were not based on the expected output of the AM, but on the use and position of supporting surfaces. Because the posture part of the AM is based on the position of the sensors with regard to the gravitational acceleration (largely determined by the position of the parts of the body to which they are attached), the interpretation of sitting in a slouching position as lying is likely to occur in some cases.

Although driving a wheelchair was not part of the protocol, this activity was detected in 272 seconds (Table I). This misdetection occurred in 37% of the time during car-driving and is probably due to the suspension of the car or to small cyclic forward-backward movements of the trunk during driving. When using the AM in future studies, one might have to correct these misdetections to sitting or general movement. Future research will focus on optimizing the detection of wheelchair driving (e.g., by filtering).

In conclusion, the AM is a valid and feasible device to quantify physical activities in patients with mild to moderate CHF. The overall agreement between the AM and reference method was high (90%), and misdetections were – besides

discrepancies in moment of onset/end of activities (which are likely to account for relatively many misdetections in protocols containing quickly alternating activities), and grey area (e.g., lying in a position between lying on the back and lying on the side) – mainly due to small differences in output categories and frame of reference between the video analysis and AM analysis. When using the device in severely affected patients (borderline III/IV and IV), the pre-set ranges for walking in the analysis software may have to be adapted. In patients with severe skin problems, alternative adhesive material has to be used. The AM is a valuable acquisition for research or clinical practice in CHF because it provides detailed information on several aspects of everyday life. Moreover, the possibility of long-term simultaneous measurement of physical activity and ECG gives the device even more value.

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