Research Report

# Validity and Reliability of Measurements Obtained With an "Activity Monitor" in People With and Without a Transtibial Amputation

**Background and Purpose.** In this study, the validity and reliability of measurements obtained with an "Activity Monitor" (AM) were examined. The instrument is designed to monitor ambulatory activity by use of accelerometer signals, and it detects several activities associated with mobility (standing, sitting, lying, transitions, movement-related activities). **Subjects.** Four men with a transtibial amputation and 4 men without a transtibial amputation participated. **Methods.** The subjects performed normal daily activities, during which accelerations were measured and videotape recordings were made (reference method). Validity was assessed by calculating agreement scores between the AM output and the videotape recordings and by comparing the number of transitions and the duration of activities determined by both methods. **Results.** The overall agreement between the AM output and the videotape recordings was 90%. Other agreement scores, in addition to the determination of the number of transitions and the duration of activities, were generally within a range of error of 0% to 10%. **Conclusion and Discussion.** The reliability and validity of the AM measurements appeared to be good, which supports its potential use in rehabilitation and physical therapy. [Bussmann HBJ, Reuvekamp PJ, Veltink PH, et al. Validity and reliability of measurements obtained with an "Activity Monitor" in people with and without a transtibial amputation. *Phys Ther.* 1998;78:989–998.]

**Key Words:** *Accelerometry, Ambulatory monitoring, Mobility, Physical activities, Validity.*

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Locomotion, ambulation, and mobility are important aspects of rehabilitation.[1-8] Many techniques are used for acquisition of mobility data, including the use of questionnaires,[9-14] observation,[10,15-17] diaries,[18-19] kinetic and kinematic systems,[16,20,21] mechanical and electronic motion sensors,[17,22-25] and types of activity monitors.[26-32] The selection of a technique depends on, among other variables, the kind of information required. If unobtrusive, reliable, and valid measurements are required for a large and specific set of mobility activities during normal daily life in a person's own environment, current techniques fail to some extent. We therefore developed an "Activity Monitor" (AM),* an instrument that can be used for long-term monitoring of ambulatory activity by use of accelerometer signals and for assessment of the quantity (when, how long, how often) and quality (how performed) of several mobility activities. These activities include stationary activities (ie, standing, sitting, and 3 different modes of lying), movement-related activities (ie, walking, climbing stairs, cycling, and using a wheelchair), and the transitions between the stationary activities. Among other types of subjects, our studies will include people with amputation of the leg, because restricted mobility is a major problem for these persons.

Until now, the development of the instrument comprised the selection of the type, number, and location of sensors and the optimization of analysis algorithms,[33,34] based on data for subjects without disease or impairment. The validity of measurements obtained with the instrument, however, needs much attention (ie, whether AM-derived measurements actually reflect the subject's activities). Validity may be influenced by factors such as age, sex, height, weight, disease or impairment, phase of rehabilitation, amputation level, and setting. The aim of this study, therefore, was to investigate the reliability and validity of AM-derived measurements obtained for persons with and without an amputation. The main research question was: Can the type and duration of activities and the number of transitions be validly measured by the AM? A secondary research question was: Does the AM function at the same level of accuracy (1) when measurements are repeated, (2) when the instrument is used with different subjects, and (3) when the instrument is used with persons with and without a transtibial amputation?

* The development started in 1992 as a joint project of Erasmus University Rotterdam (Department of Rehabilitation), University of Twente (Department of Electrical Engineering), and an industrial partner, all from the Netherlands.

## Method

### *Activity Monitor*

The AM consists of accelerometers, a portable data recorder, and a computer with analysis programs. In this study, IC-3031 uniaxial piezo-resistive accelerometers† (1.5 × 2 × 0.5 cm) were used. The signals of these sensors consist of both a component of the gravitational acceleration and a component of other accelerations, if present.[33,34] The magnitude of these components depends on the direction of these accelerations with regard to the sensitive axis of the sensor and their magnitudes.

Four sensors were fixed on the skin by means of double-sided tape. Two sensors were attached on the front of the thighs, halfway between the anterior superior iliac spine and the upper side of the patella, and 2 sensors were attached on the lower part of the sternum, perpendicular to each other (Fig. 1). The trunk sensors were also held in place by means of a rubber belt. All accelerometers were attached as parallel as possible to the vertical or horizontal plane; a maximum deviation of 15 degrees

† Supplied by Becker Ingenieurbüro, Karl-Seckinger. Strasse 48, D-7500 Karlsruhe 41, Germany.



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This research was part of the EUREKA Project DYNAPORT, which was financed, in part, by the Dutch Ministry of Economic Affairs.

*This article was submitted July 30, 1997, and was accepted February 24, 1998.*

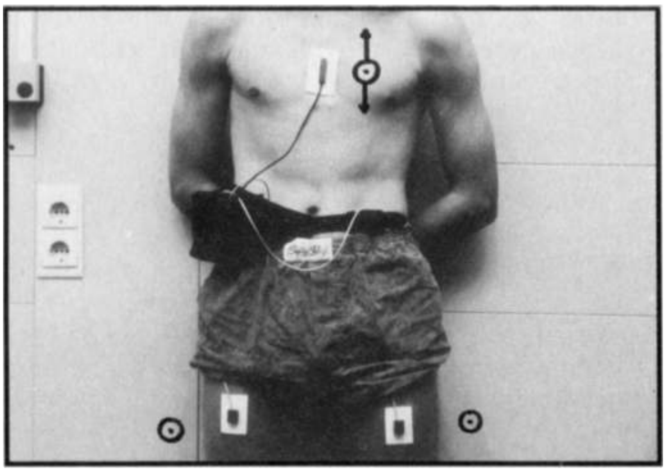

**Figure 1.**
The accelerometers and portable recorder attached to the body. In this study, only one leg accelerometer was used. The arrows and circles (axis in/out the paper) indicate the direction (longitudinal and tangential, respectively) of the sensitive axis of the accelerometers of the thigh (1 sensor) and the trunk (2 sensors) while standing.

was allowed. Each accelerometer was connected to a portable Vitaport 1 data recorder† (13 × 9 × 4 cm, 480 g, battery included) by a cable (under the clothes) and a Lemo-jacket.† The recorder was worn on a belt around the subject's waist. Power was delivered by a rechargeable battery (270 mAh, 4.8 V). Raw signals were digitally stored on a removable memory card, with a sampling frequency of 25 Hz.

After the measurements, the data were downloaded to a Macintosh IIci computer‡ for analysis. Although the signals of 4 sensors were measured, the signal of the left or amputated leg was not used in the analysis. The signal of the other leg was measured to study the quality of walking. The data were analyzed by means of Vitagraph§ Signal Processing and Inferencing Language (SPIL).[35,‖]

The output of the AM is the automatic 1-second selection of one type of activity (Fig. 2). To achieve this output, 2 types of signals were derived from each sensor signal: (1) a low-pass filtered (0.5 Hz) signal (3 LP signals) and (2) a successively high-pass filtered (0.5 Hz), rectified, and smoothed signal (3 HPRS signals). The LP signals were used to distinguish 5 stationary activities, because these activities have a unique combination of 3 LP signals. The HPRS signal of the thigh was used to distinguish between movement-related and stationary activities. Movement-related activities are characterized by variability of the accelerometer signal. The more "energetic" an activity, the more variable the accelerometer signal and the higher the value of the HPRS signal. The way in which the movement-related activities can be distinguished from each other is still under investigation. This study, therefore, was restricted to the global categories "stationary" and "movement-related," the 5 stationary activities, and the transitions.

### Reference Method

Videotape recordings were chosen as the reference method, or standard. During all measurements, videotape recordings (with a video clock) were made, together with the monitoring of AM output. To allow a correct comparison of the videotape and AM data, the timing of both instruments was synchronized. The videotape recordings were made and analyzed by the same person (a medical student during her research traineeship), independent from the AM analysis. In a later study,[36] we investigated the interrater reliability of data from the videotape analysis. An overall agreement of 99.7% was found between 2 raters, indicating the reliability of the data from the videotape analysis.

The classification categories of the videotape analysis were the same as the classification categories of the AM analysis, and the output signals of both instruments had the same 1-second time resolution. The guidelines for the videotape analysis, however, were different from the guidelines for the AM analysis. The videotape analysis of lying, sitting, and standing was based on the presence and position of supporting surfaces, whereas the detection of posture with the AM was based on the angular position of the thighs and the trunk. Furthermore, in the videotape analysis, only cyclic activities (walking, climbing stairs, cycling) were determined as movement-related, whereas the AM may also determine noncyclic activities as movement-related. After synchronization to the signals in the AM file, the videotape recording time was converted to sample numbers. These sample numbers and their corresponding category codes were edited so that they could be transferred to a signal in the AM file (Fig. 2).

### Protocol

The measurements were taken in a seminatural setting in the occupational therapy department, in which a complete (representative) apartment had been installed. During the measurements, the subjects performed several functional activities, including dressing, going to bed, preparing breakfast, peeling and cooking potatoes, watching television, reading a newspaper, shopping on another floor after climbing a stairway, and riding a bicycle (using a wheelchair was not included). These activities were selected by an occupational therapist. Before the measurements, the protocol was explained to the subjects. When the measurements were taken, sub-

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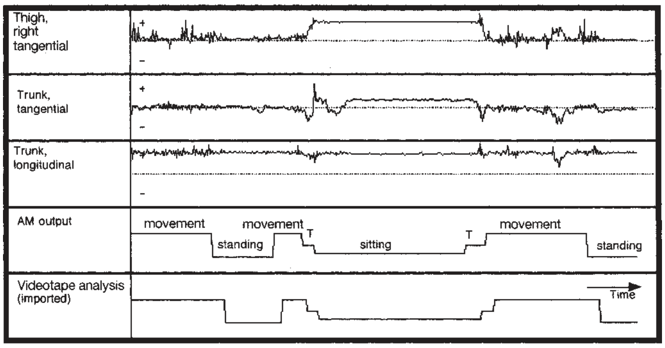


**Figure 2.**
Example of the measured accelerometer signals during a 2-minute measurement period with some activities. The fourth curve is the output of the Activity Monitor (AM), with each activity category represented by his own level (T=transition). The lower curve shows the imported videotape analysis, used as reference in the calculation of the agreement scores.

jects were allowed to do the activities in their own way and at their own pace. The measurements were planned to last approximately 45 minutes.

### *Subjects*

The following inclusion criteria were used for the subjects with an amputation: one-sided transtibial amputation, recent (<6 months) discharge from an outpatient rehabilitation clinic, age greater than 18 years, no use of assistive devices, ability to complete the protocol, and no diseases or impairments disturbing locomotion. A rehabilitation specialist selected 4 men from a file of discharged patients (mean age=32 years, SD=17.7, range=19–57; mean height=1.82 m, SD=0.05, range=1.75–1.85; mean weight=74 kg, SD=9.2 range=63–83). For each patient, a person without an amputation and of the same sex, age (±10 years), weight (±10 kg), and height (±0.10 m) was selected. The patients performed the protocol once, and the comparison subjects performed the protocol twice on different days to determine test-retest reliability. A total of 12 measurements were performed.

### *Data Analysis*

Both the AM output signal (with AM activity category codes) and the videotape analysis signal (with the videotape activity category codes) had a time resolution of 1 second. Every second, the codes of both signals could be compared. In this way the number of corresponding and noncorresponding counts (1 count=1 second) and the agreement scores could be calculated. Because the videotape analysis can be regarded as a standard, the following agreement scores—as validity measures of the AM—were used (research question 1):

1. *Agreement:* the percentage of agreement between all samples of videotape recording and AM data. Agreement was calculated according to the equation: agreement=(number of identical samples of videotape recording data and AM data/total number of samples) × 100%.
2. *Sensitivity:* the degree to which each videotape activity category (representing the activities actually performed) was detected correctly by the AM. Sensitivity was calculated according to the equation: sensitivity for videotape activity category A=(number of identical samples of videotape recording data and AM data when videotape activity category is A/total number of samples for videotape activity category A) × 100%.
3. *Predictive value:* the degree to which each AM activity category agreed with the videotape activity category (representing the activities actually performed). Predictive value was calculated according to the equation: predictive value of AM activity category A=(number of identical samples of videotape recording data and AM data when AM activity category is A/total number of samples for AM activity category A) × 100%.

The 1-second output of the AM and videotape recording analysis allowed calculation of duration (in seconds) per activity. The number of transitions within each transition category was calculated from identified changes in posture. All calculations and comparisons were done automatically by means of SPIL software.

Simple descriptive statistical measures, such as weighted (corrected for duration of activities) mean and standard deviation, were used to describe group results. The Wilcoxon matched-pairs signed-rank test was used to show systematic differences in results between the videotape recording analysis and the AM analysis. The Mann-Whitney *U* test was used to show systematic differences in results between the patient group and the first measurement of the comparison group. All statistical analyses were done with SPSS 5.0 for MS Windows.[#] A probability value of $P<.05$ was considered to indicate a significant effect.

## Results

The overall agreement between the videotape data and the AM output was 90%. The overall (weighted) mean of most sensitivities and predictive values equaled or exceeded 90% (Tabs. 1 and 2). The overall sensitivity for lying on the side and for movement-related activities was somewhat lower (88% and 85%, respectively), as was the overall predictive value of the AM activity categories of sitting and movement-related activities (88% and 89%, respectively). During 890 seconds, standing (determined by videotape analysis) was detected by the AM as a

[#] SPSS Benelux BV, PO Box 115, 2200 AC Gorinchem, the Netherlands.

**Table 1.**
Number of Corresponding (Underlined) and Noncorresponding (Plain) Counts (1 Count=1 Second) of Videotape Activity and Activity Monitor (AM) Output Added for All Measurements[a]

| Videotape Activity | AM Output: Lying on Back | Lying on Side | Lying Prone | Standing | Sitting | Movement-Related Activity | Total | Overall Sensitivity (%) |
|---|---|---|---|---|---|---|---|---|
| Lying on back | 853 | 0 | 0 | 0 | 53 | 15 | 921 | 93 |
| Lying on side | 0 | 1,057 | 0 | 5 | 118 | 20 | 1,200 | 88 |
| Lying prone | 0 | 0 | 67 | 0 | 0 | 1 | 68 | 99 |
| Standing | 0 | 0 | 0 | 8,755 | 83 | 890 | 9,728 | 90 |
| Sitting | 0 | 0 | 0 | 0 | 4,809 | 108 | 4,917 | 98 |
| Movement-related activity | 27 | 20 | 5 | 916 | 421 | 8,068 | 9,457 | 85 |
| Total | 880 | 1,077 | 72 | 9,676 | 5,484 | 9,102 | 26,291 | |
| Overall predictive value (%) | 97 | 98 | 93 | 90 | 88 | 89 | | 90 |

[a] The last column shows the overall sensitivity of the AM for each videotape activity category; the bottom row shows the overall predictive value of each AM activity category.

**Table 2.**
Percentages per Measurement, Representing the Sensitivity (S) and Predictive Value (PV)[a]

| Subject/ Measurement | Sensitivity and Predictive Value (%): Lying on Back | | Lying on Side | | Lying Prone | | Standing | | Sitting | | Movement-Related Activity | | Agreement (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | PV | S | PV | S | PV | S | PV | S | PV | S | PV | |
| H1M1 | ... | ... | 99 | 99 | ... | ... | 90 | 90 | 97 | 95 | 86 | 87 | 91 |
| H2M1 | 100 | 97 | 100 | 98 | ... | ... | 77 | 91 | 98 | 97 | 93 | 85 | 90 |
| H3M1 | 94 | 91 | 100 | 91 | ... | ... | 91 | 97 | 95 | 82 | 91 | 90 | 92 |
| H4M1 | ... | ... | 93 | 99 | ... | ... | 77 | 90 | 97 | 87 | 88 | 80 | 86 |
| $\bar{X}$ | 97 | 93 | 97 | 98 | ... | ... | 85 | 92 | 97 | 92 | 90 | 85 | 90 |
| H1M2 | 100 | 99 | 95 | 100 | ... | ... | 92 | 91 | 99 | 94 | 88 | 92 | 93 |
| H2M2 | 100 | 95 | 16 | 88 | ... | ... | 77 | 96 | 98 | 74 | 94 | 86 | 85 |
| H3M2 | 97 | 98 | ... | ... | ... | ... | 90 | 92 | 98 | 92 | 89 | 90 | 92 |
| H4M2 | ... | ... | 99 | 100 | ... | ... | 85 | 88 | 94 | 91 | 90 | 88 | 90 |
| $\bar{X}$ | 98 | 98 | 70 | 99 | ... | ... | 86 | 92 | 97 | 87 | 91 | 89 | 90 |
| A1M1 | ... | ... | 98 | 98 | 99 | 93 | 97 | 89 | 98 | 97 | 80 | 93 | 92 |
| A2M1 | 61 | 100 | ... | ... | ... | ... | 97 | 92 | 97 | 69 | 73 | 92 | 88 |
| A3M1 | 100 | 97 | 95 | 95 | ... | ... | 95 | 94 | 100 | 87 | 80 | 92 | 92 |
| A4M1 | 99 | 96 | 100 | 98 | ... | ... | 96 | 80 | 100 | 95 | 71 | 94 | 88 |
| $\bar{X}$ | 86 | 97 | 99 | 98 | 99 | 93 | 96 | 89 | 99 | 86 | 76 | 93 | 90 |
| $\bar{X}$ (overall) | 93 | 97 | 88 | 98 | 99 | 93 | 90 | 90 | 98 | 88 | 85 | 89 | 90 |

[a] Ellipsis indicates that the activity was not performed or detected. The weighted means for each subgroup are calculated. In the last column, the agreement per measurement is shown; in the last row, the weighted overall means are shown. Measurement code: H1–H4=subjects without amputation, A1–A4=subjects with transtibial amputation, M1 and M2=measurements 1 and 2.

movement-related activity. During 916 seconds, however, movement-related activities (determined by videotape analysis) were detected by the AM as standing. Table 1 also provides insight on the distribution of activities during the measurements. No differences in distribution of activities existed between the groups, although the measurements in the patient group lasted, on average, longer than those in the comparison group (41 and 34 minutes, respectively).

The AM slightly overestimated the total number of transitions compared with the videotape recordings (overall difference: +16 [+7%], $P<.05$, Tab. 3). The overall duration of activities determined by the AM did not deviate from the duration of activities determined by videotape analysis for standing (Tab. 4). The duration of sitting was overestimated by the AM (mean difference=2.2%, $P<.01$).

The standard deviation of the difference in agreement between the first and second measurements for the comparison subjects was 3.9% (range=−5%–4%). The standard deviations for the percentage of agreement

**Table 3.**
The Number of 6 Transition Types, Determined by Activity Monitor (AM) and Videotape Analysis (V)[a]

| Subject/ Measurement | No. of Transitions: Lying-Sitting V | AM | Lying-Standing V | AM | Sitting-Lying V | AM | Sitting-Standing V | AM | Standing-Lying V | AM | Standing-Sitting V | AM | Total V | AM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H1M1 | 0 | 0 | 1 | 1 | 0 | 0 | 8 | 9 | 1 | 2 | 9 | 9 | 19 | 21 |
| H2M1 | 1 | 2 | 0 | 0 | 0 | 1 | 9 | 9 | 1 | 1 | 8 | 8 | 19 | 21 |
| H3M1 | 1 | 1 | 0 | 0 | 0 | 1 | 9 | 9 | 1 | 0 | 8 | 9 | 19 | 20 |
| H4M1 | 0 | 0 | 1 | 2 | 1 | 1 | 7 | 8 | 0 | 1 | 8 | 9 | 17 | 21 |
| Total | 2 | 3 | 2 | 3 | 1 | 3 | 33 | 35 | 3 | 4 | 33 | 35 | 74 | 83 |
| H1M2 | 0 | 0 | 1 | 1 | 0 | 0 | 7 | 7 | 1 | 1 | 7 | 7 | 16 | 16 |
| H2M2 | 1 | 1 | 0 | 0 | 0 | 0 | 12 | 12 | 1 | 1 | 11 | 11 | 25 | 25 |
| H3M2 | 1 | 1 | 1 | 1 | 1 | 1 | 8 | 8 | 1 | 1 | 8 | 8 | 20 | 20 |
| H4M2 | 0 | 0 | 1 | 1 | 1 | 1 | 5 | 6 | 0 | 0 | 6 | 7 | 13 | 15 |
| Total | 2 | 2 | 3 | 3 | 2 | 2 | 32 | 33 | 3 | 3 | 32 | 33 | 74 | 76 |
| A1M1 | 1 | 1 | 0 | 0 | 1 | 1 | 8 | 7 | 0 | 0 | 8 | 7 | 18 | 16 |
| A2M1 | 2 | 2 | 0 | 0 | 2 | 2 | 8 | 10 | 0 | 0 | 8 | 10 | 20 | 24 |
| A3M1 | 1 | 1 | 0 | 0 | 1 | 1 | 5 | 5 | 0 | 0 | 5 | 5 | 12 | 12 |
| A4M1 | 0 | 0 | 1 | 1 | 0 | 1 | 7 | 8 | 1 | 0 | 7 | 9 | 16 | 19 |
| Total | 4 | 4 | 1 | 1 | 4 | 5 | 28 | 30 | 1 | 0 | 28 | 31 | 66 | 71 |
| Total (overall) | 8 | 9 | 6 | 7 | 7 | 10 | 93 | 98 | 7 | 7 | 93 | 99 | 214 | 230 |

[a] The data are shown per measurement, for each subgroup, and for all measurements together. Measurement code: H1–H4=subjects without amputation, A1–A4=subjects with transtibial amputation, M1 and M2=measurements 1 and 2.

**Table 4.**
Duration (as Percentage of the Measurement Time) of Each Activity Category, Determined by Activity Monitor (AM) and Videotape Analysis (V)[a]

| Subject/ Measurement | Duration (%): Lying on Back V | AM | Lying on Side V | AM | Lying Prone V | AM | Standing V | AM | Sitting V | AM | Movement-Related Activity V | AM | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H1M1 | 0.0 | 0.0 | 9.0 | 8.9 | 0.0 | 0.0 | 36.9 | 36.8 | 23.0 | 23.4 | 31.1 | 30.9 | 100 |
| H2M1 | 1.7 | 1.8 | 5.7 | 5.9 | 0.0 | 0.0 | 29.9 | 25.2 | 19.0 | 19.1 | 43.7 | 48.1 | 100 |
| H3M1 | 2.6 | 2.7 | 2.5 | 2.8 | 0.0 | 0.0 | 44.5 | 41.9 | 10.9 | 12.6 | 39.6 | 40.1 | 100 |
| H4M1 | 0.0 | 0.0 | 9.3 | 8.8 | 0.0 | 0.0 | 35.3 | 29.9 | 17.5 | 19.6 | 37.8 | 41.7 | 100 |
| $\bar{X}$ | 1.0 | 1.1 | 6.7 | 6.6 | 0.0 | 0.0 | 36.6 | 33.5 | 17.8 | 18.8 | 37.9 | 40.0 | 100 |
| H1M2 | 5.3 | 5.4 | 4.3 | 4.1 | 0.0 | 0.0 | 30.2 | 30.7 | 26.4 | 27.6 | 33.8 | 32.3 | 100 |
| H2M2 | 3.9 | 4.1 | 6.7 | 1.2 | 0.0 | 0.0 | 27.4 | 22.2 | 21.1 | 27.6 | 40.9 | 44.9 | 100 |
| H3M2 | 10.9 | 10.8 | 0.0 | 0.0 | 0.0 | 0.0 | 33.5 | 33.0 | 15.5 | 16.6 | 40.1 | 39.6 | 100 |
| H4M2 | 0.0 | 0.0 | 9.3 | 9.2 | 0.0 | 0.0 | 34.3 | 32.9 | 15.1 | 15.7 | 41.3 | 42.2 | 100 |
| $\bar{X}$ | 5.1 | 5.1 | 5.0 | 3.5 | 0.0 | 0.0 | 31.3 | 29.6 | 19.6 | 22.1 | 39.0 | 39.8 | 100 |
| A1M1 | 0.0 | 0.0 | 2.7 | 2.7 | 3.0 | 3.1 | 39.4 | 43.0 | 25.5 | 26.0 | 29.4 | 25.1 | 100 |
| A2M1 | 4.9 | 3.0 | 0.0 | 0.0 | 0.0 | 0.0 | 49.2 | 51.6 | 14.4 | 20.3 | 31.6 | 25.2 | 100 |
| A3M1 | 7.3 | 7.6 | 1.9 | 1.9 | 0.0 | 0.0 | 36.9 | 37.2 | 23.5 | 26.9 | 30.4 | 26.4 | 100 |
| A4M1 | 4.6 | 4.8 | 5.8 | 5.9 | 0.0 | 0.0 | 40.3 | 48.1 | 13.0 | 13.7 | 36.3 | 27.5 | 100 |
| $\bar{X}$ | 4.2 | 3.8 | 2.4 | 2.5 | 0.7 | 0.7 | 42.0 | 45.5 | 18.7 | 21.6 | 31.9 | 26.0 | 100 |
| $\bar{X}$ (overall) | 3.5 | 3.3 | 4.6 | 4.1 | 0.3 | 0.3 | 37.0 | 36.8 | 18.7 | 20.9 | 36.0 | 34.6 | 100 |

[a] The data are shown per measurement, and weighted means are calculated for the subgroups and for all measurements together. Measurement codes: H1–H4=subjects without amputation, A1–A4=subjects with transtibial amputation, M1 and M2=measurements 1 and 2.

ranged from 2.3% (range=88%–92%) in the patient group to 3.6% (range=85%–93%) for the second measurement in the comparison group. When all measurements were included, the standard deviation was 2.6% (range=85%–93%).

To examine differences in functioning of the AM in persons with and without transtibial amputation, variables were compared between the patient group and the comparison group (first measurement). The agreement did not differ between groups. Some percentages, however, for sensitivity and predictive value differed (Tab. 2). The sensitivity for standing and the predictive value for standing were higher in the patient group than in the comparison group, and the sensitivity for movement-related activities was higher in the comparison group than in the patient group ($P<.03$).

The functioning of the AM, expressed as the correct determination of the number of transitions, did not differ between groups (Tab. 3). The duration of movement-related activities was overestimated by the AM in the comparison group (+2.1%) and underestimated in the patient group (−5.9%). The duration of standing was underestimated in the comparison group (−3.1%) and overestimated in the patient group (+3.5%).

## Discussion

The agreement scores in this study were generally within a range of error of 0% to 10%. A comparison of the results of our study with those of other studies and instruments is not possible because the different instruments used in these studies discriminate among different activity categories,[26–28,37] the protocols consisted of different activities,[29,32] or validity was calculated following another or unknown method.[30,31,38] Kiani et al[38] have developed the "Ambulatory Monitoring of Motor Activities" (AMMA) system using accelerometers and an artificial neural network. The set of activities that can be detected with the AMMA system are similar to the activity categories of the AM. Although the technique seems promising and 95% reliability is reported, the validation technique used is questionable. The measured accelerometer signals were the input of both the AMMA system and the reference method (visual interpretation of the signals). Walker et al[37] reported a validation study of an activity monitor based on mercury switches and accelerometers. Validation was studied in terms of steps counted; validation of body positions was not reported. Stock and colleagues[30,31] used a "microcomputer-based system for the assessment of postoperative fatigue" consisting of a posture timing module, an activity module, and a heart rate module. Although they reported maximum error percentages of about 5%, they did not clearly describe how these percentages were obtained, and the results, therefore, are difficult to interpret.

Anastasiades and Johnston[26] used electromyography to discriminate between stationary and movement-related activities. Stationary activities could not be distinguished from each other, and interindividual comparisons appeared to be difficult. Fahrenberg et al[29] applied accelerometer sensors and a hydrostatic tube to monitor their subjects' ambulatory activity. The same sensors were applied by Tuomisto et al,[32] who also used electromyography. In both studies, only a small number standardized activities were performed to determine validity. Instruments for measuring walking periods were validated by Bassey et al.[27] Although the measurements they obtained showed reasonable validity, the instruments they used measured only walking and stair-climbing performance; these instruments were not designed to measure cycling and different body positions. Several workers[17,39–41] used accelerometry to distinguish between stationary and movement-related activities and to determine the level of activity. Due to the limited scope of these instruments, comparison with the AM is not useful. The instrument used by Diggory et al[28] is designed with a tilt switch to measure time in the upright position. Although their validity study gave good results, possible errors were reported for measurements obtained when the subjects were lying prone, cycling, and climbing stairs. Furthermore, movement-related activities formed no part of the output of the instrument.

Some arguments against the present study can also be posed. The activities were prescribed and limited in number, and they were performed in the same environment—an artificial environment, not the subjects' home environment. The subjects selected for the patient group had transtibial amputations and had finished rehabilitation. Furthermore, they were relatively good walkers, and 3 of the 4 subjects in this group were fairly young. In our view, the generalizability of the results of our study to unsupervised measurements is enhanced by some other characteristics of the study. The measurements were done in a seminatural setting, and the activities were functional and selected by an occupational therapist who did not participate in the study. The subjects could perform the activities in their own manner, and the method for assessing the validity of the measurements was critical. If the AM is to be used in the real-world environment of patients (eg, with external vibrations due to car or train, extension of the kinds of movements and postures[17,42]) and with patients with other movement patterns[43] (eg, other impairments, other amputation levels, other phases of rehabilitation, different ages), however, further study of the reliability and validity of measurements obtained with the device is needed. In later validation studies of the AM, used with patients with failed back surgery in their own environment[44] and with subjects without known disease or impairment in the setting of a psychophysiological study,[36] results similar to those of our study were obtained. Overall percentages of agreement of 87% and 88% were found, respectively, supporting the validity of the measurements and the robustness of the AM.

While we were taking the measurements in our study, there were no problems with either the sensors or the recorder system, and neither the cables nor the recorder interfered with any of the subjects' activities. We observed, however, a tendency of the sensors (especially the trunk sensors) to come somewhat loose from the skin, probably due to chest hair, perspiration, or the rubber belt. In later studies,[36,44] therefore, we taped the sensors onto the skin with other material (eg, Kushionflex[**]). The method of fixation of the sensors is still a focus of our research interest.

Recently, we obtained measurements (1–2 days) with a recorder of slightly greater size and weight than that used in the present study and found that the measurement system may cause some discomfort. The system cannot be used in a wet environment (eg, while bathing or taking a shower). Some people find the recorder or the cables disturbing while sleeping or while dressing or undressing, and some people dislike being seen wearing the instrument. Therefore, we are investigating methods that will allow patients to easily attach and remove the recorder and sensors themselves, without compromising the measurements. Reducing the weight and size of the recorder may also increase comfort and applicability. Five prototypes of a new recorder (RAM[††]), of approximately the same size and weight as the recorder used in our study, have been developed to enable continuous measurement of accelerometer signals for more than 48 hours (compared with approximately 2 hours for the recorder used in our study), without replacement of flash cards or batteries. The recorder receives power from 4 penlight batteries and allows measurement of up to 8 signals. Data are stored on a flash card of 40 MB (or more). Reading the data from the flash card takes about 1 minute. The analysis of data (for a 2-day measurement) takes less than 1 hour. Generally, we start the measurements in the patient's home, and the data are downloaded in our laboratory. Downloading the data by telephone is now an option.

The AM was not free of errors. The investigation of even small errors can be used to increase knowledge about the functioning of the AM. Relatively often, standing (according to videotape analysis) is detected as a movement-related activity by the AM, whereas some movement-related activities (according to videotape analysis) are detected as sitting or standing by the AM (Tab. 1). The distinction between the 2 global categories of stationary and movement-related activities occurs early in the analysis program. Errors at this point have irreversible consequences for subsequent phases of the activity detection. Furthermore, small time shifts between videotape and AM signals, infrequent activities that were difficult to analyze using videotape recordings, and timing inaccuracies in videotape analysis (as shown in Fig. 2) may have some effect on these errors. The interrater reliability of data from the videotape analysis in a similar study performed later,[36] however, showed a percentage of agreement of 99.7%. The effect of videotape analysis errors on the data will be small, and that result showed that the videotape recording can be used as a standard. Other causes were shown to be more important.

The detection of an activity as stationary or movement-related strongly depends on an adjustable threshold applied on the HPRS signal of the leg, and the setting of this threshold is a matter of optimization. The detection of standing as a movement-related activity (eg, due to leg movement during standing, but not walking) and the detection of movement-related activities as standing (eg, due to shuffling) are quantitatively important misinterpretations. They lead to a decrease in overall agreement of about 6%. Generally, however, the threshold seemed well-chosen, as can be concluded from the small difference (−1.4%) between the duration of movement-related activities determined by AM and videotape recordings and the almost equal number of counts of the detection of movement-related activities as standing and of the detection of standing as a movement-related activity.

A movement-related activity was rather frequently (421 seconds) determined as sitting (Tab. 1). Cycling appeared to be the main activity that caused this discrepancy. During cycling, there were periods when the subjects did not move their legs. These periods were periods of movement-related activity according to videotape analysis, whereas the AM detected sitting. Furthermore, if the legs were moving during cycling, the acceleration energy was sometimes too low to cause the detection of movement-related activities. To quantify the effect of these errors, we studied the occurrence of these errors. The determination of a movement-related activity such as sitting was, for about 300 seconds of output, explained by these errors. If these errors had not occurred, the sensitivity of movement-related activities would have increased from 85% to 88% and the predictive value for sitting would have increased from 88% to 93%.

If decision errors for stationary and movement-related activities are excluded (ie, the "movement-related activity" row and column in Tab. 1 are not included in the analysis), the quality of the stationary activity detection can be assessed. The overall agreement then increases to 98%, and most sensitivities and predictive values equal, or come close to, 100%. Only the overall sensitivity for lying on the back (94%) and lying on the side (90%) and the overall predictive value of sitting (95%) are then clearly lower than 100%. This finding is due to 2 misinterpretations. In one comparison subject (H2M2, 118 seconds), lying on the side with the upper side of the

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trunk elevated and the legs rotated (while reading a book) was detected as sitting. In one patient (A2M1, 53 seconds), lying on the back (according to the criteria of the videotape analysis) with the trunk supported by a few pillows was also detected as sitting.

The total number of transitions was slightly, but systematically, overestimated by the AM. This finding was mainly due to overestimation of the sitting-to-standing and standing-to-sitting transitions (eg, foot on a chair while donning and doffing shoes and socks [videotape: standing; AM: standing-sitting-standing]) and to overestimation of more complex transitions (eg, from standing to lying on the back via sitting and lying on the side). The duration of sitting also was overestimated. When data are corrected for the 2-fold misinterpretation of stationary activities and the determination of cycling as sitting, a considerable improvement is reached. Existing differences in duration (last row, Tab. 4) will almost disappear.

The differences in the agreement scores between the first and second measurements of the 4 comparison subjects were small, as were the differences in agreement scores among subjects within the same group, even though considerable individual differences in performance were observed. The mean agreement was the same for the patient group and the comparison group (90%). Comparison of the 2 groups, however, revealed some differences in results. In general (also after correction for the determination of cycling as sitting), movement-related activities were overestimated in the comparison group (+2.1%) but underestimated in the patient group (−5.9%). Standing, however, was overestimated in patient group (+3.5%) but underestimated in the comparison group (−3.1%). These differences between groups were statistically significant. The data suggest that the subjects with transtibial amputations in this study walked, cycled, and climbed stairs less energetically (ie, with less acceleration variation) than did the comparison subjects.

The potential of the AM can be increased by simultaneous measurement of, for example, electrocardiographic activity in quantifying strain, or markers. Furthermore, we assume that the accelerometer signals contain much information on the quality of the activities (how performed). Our research focuses especially on the quality of walking (spatiotemporal variables, stability).

There may be a considerable interday and intersubject variability,[14,27,45] which may differ by patient group. This variability will determine the number of days over which measurements should be taken and the number of subjects included in group studies. Future studies should investigate these 2 types of variability.

The AM is an instrument that provides data on the activities a patient actually performs during daily life. Generally, in many medical disciplines and also in physical therapy, the decisions about treatment and the evaluation of that treatment are increasingly attuned to and related to functional performance. For example, the effectiveness of physical therapy is determined not only by the change in joint mobility but also by changes in the performance of activities of daily living. The usefulness of the AM in physical therapy intervention, therefore, will depend on the treatment goals. The AM can be a powerful instrument in evaluative studies, especially when the formulated goals are related to the quantity of movement and postures. We believe that the AM will first be used in research. After making the instrument more dedicated, improving its usability, and reducing its costs, however, we expect that the AM will also be used in the practice of physical therapists.

## Conclusion

Activity monitoring by means of accelerometry proves to be a promising method to obtain reliable and valid measurements of the activities a patient actually performs during daily life, which is essential in rehabilitation and physical therapy. Research with less obtrusive devices in real-world settings is now needed.

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