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Detection of posture and motion by accelerometry: a validation study in ambulatory monitoring

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Abstract

The suitable placement of a small number of calibrated piezoresistive accelerometer devices may suffice to assess postures and motions reliably. This finding, which was obtained in a previous investigation, led to the further development of this methodology and to an extension from the laboratory to conditions of daily life. The intention was to validate the accelerometric assessment against behavior observation and to examine the retest reliability. Twenty-four participants were recorded, according to a standard protocol consisting of nine postures/motions (repeated once) which served as reference patterns. The recordings were continued outside the laboratory. A participant observer classified the postures and motions. Four sensor placements (sternum, wrist, thigh, and lower leg) were used. The findings indicated that the detection of posture and motion based on accelerometry is highly reliable. The correlation between behavior observation and kinematic analysis was satisfactory, although some participants showed discrepancies regarding specific motions. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Ambulatory monitoring; Accelerometer; Movement; Physical activity; Posture

1. Introduction

The assessment of posture and motion is an essential issue in ambulatory monitoring because physiological responses, such as changes in heart rate or blood pressure, may result from changes in body position and physical activity. Continuous 24-h recordings of posture and motion can be generally useful in behavior assessment (Fahrenberg & Myrtek, 1996).

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The assessment of posture, motion and physical activity will depend on the specific aims of a given study. Among these are:

1. detection of change in body position (e.g. lying supine, sitting, standing) and in body rotation (e.g. during sleep);
2. kinematic analysis, i.e. discrimination of certain patterns of movement (e.g. gait) or of symptoms (e.g. hand tremor, restless legs);
3. discrimination of distinct states (e.g. supine rest, physical exercise);
4. derivation of an overall activity index which provides useful indication of the subject's activity level for the 24-h period;
5. estimation of the momentary metabolic rate (energy expenditure);
6. measurement of relative height of a sensor (e.g. finger-cuff for blood pressure measurement in relation to the level of the heart);
7. recording of specific activities that might invalidate the measurement of other response systems (movement artifacts).

Accordingly, the methods for assessing physical activity vary considerably with respect to type and positioning of sensor, number of recording sites (channels), signal processing (e.g. filtering), and statistical procedures. Most investigators use either electromyographic recordings or accelerometer recordings. The registration of the surface electromyogram (EMG) requires the selection of a suitable recording site, preparation of the skin, and application of electrolyte and electrodes allowing for local hydration, as well as amplification, filtering, and rectification of the raw signal and, finally, processing of the EMG by integration or contour following method (cf. Fridlund & Cacioppo, 1986). Although the EMG is measured in μVolts, an absolute calibration for between-subject designs is not possible because the measurement depends on electrode positioning and individual differences in morphology and muscular function.

The accelerometer is a widely used method because of its ease of application (Tryon, 1991). However, the available accelerometers differ in relevant technical aspects even among piezoelectric sensors: general and axial sensitivity (uni-, bi- or triaxial), frequency range, resonant frequency, damping, and temperature drift. In many instances, such specifications are not given by manufacturers. The directional sensitivity is not an all-or-none characteristic but has to be measured by relating signal amplitude and angle of inclination. The available accelerometers, furthermore, differ in size and mass, durability, and price.

It should be noted that the flat design of most sensors suggests that such sensors are attached to the body surface so that the axial orientation is defined. The positioning must be designed with care especially for uniaxial sensors because the response characteristics depend on the degree of inclination between axis and direction of movement (acceleration). Conventionally used accelerometers differ essentially in their axial sensitivity (change in mV/degree of inclination).

Accelerometer recordings have to be sampled, amplified, and filtered, so that, finally, an index of physical activity can be derived. The use of a triaxial accelerosensor may be open to scrutiny if the output is summed up instead of providing three distinct signals. A psychophysiological laboratory usually does not have the technical means for calibrating an accelerometer, so that a between-subject comparison seems to be questionable, although some manufacturers state sensor sensitivity in terms of the gravitational constant g (mV/g). The placement and the degree of rigidity or flexibility in fixation of the sensor to the skin will inevitably produce a damping, i.e. a pre-filtering of the signal to an unknown extent.

Both the EMG and the conventional accelerometer should be seen as semi-quantitative methods. Indices derived from such recordings, therefore, will be more suited to within-subject designs. A detailed review on the measurement of physical activity in medicine and psychology is provided in the book by Tryon (1991). Multi-channel recordings are very seldom.

Multichannel accelerometry using calibrated devices appears to have important advantages as compared to conventional methods, that is recording the EMG or the output from non-calibrated accelerometer devices (cf. Fahrenberg, Müller, Foerster & Smeja, 1996; Patterson, Krantz, Montgomery, Deuster, Hedges & Nebel, 1993; Tuomisto, Johnston & Schmidt, 1996; Tryon, 1991). The wide bandwidth of recently available piezoresistive accelerometers have made it possible to develop a new methodology of kinematic analysis. The slow component (direct current [DC] component, i.e. signal output <0.5 Hz) allows the assessment of slow motion and change in position in relation to the gravitational axis; the alternating current (AC) component, calibrated in $\boldsymbol{g}$, represents acceleration along the sensitive axis of the device (Busser, 1994; Bussmann, Tulen, van Herel & Stam, 1998; Fahrenberg, Foerster, Müller & Smeja, 1997; Jain, Martens, Mutz, Weiß & Stephan, 1996; Martens, 1994; van Someren et al., 1998; Veltink & van Lummel, 1994).

This new methodology was used in a previous study to evaluate reliabilities and the discrimination between positions and motions. Recordings were made of 26 participants in eight conditions: sitting, standing, lying supine, sitting and typing on a PC keyboard, walking, climbing stairs, walking downstairs, and cycling. This procedure was repeated in reversed order. A classification of physical activities, according to the eight conditions and based on four parameters, that is, DC-components trunk, thigh, lower leg, and AC-component trunk, was correct in almost 100% of patterns, when it was applied to the second trial (Fahrenberg et al., 1997).

These findings speak in favour of a tentative extension of this methodology from the semi-natural conditions used in our laboratory to daily life, i.e. assessment of posture and motion during ambulatory monitoring. The present study was thus designed as an extension and, moreover, as a validation study. The question was put as to whether the findings of automatic detection of posture and motion are consistent with behavior observation. Again, a standard protocol was obtained, again, in the laboratory as a reference. Then the participant continued his daily activities outside the laboratory. He returned to the laboratory later so that the standard protocol could be repeated. This design allowed for the evaluation of retest reliability of the individual measures and the retest reliability of the classification, respectively.

The correlation between behavior observation and kinematic analysis was of central interest. Discrepancies between methods, for example, regarding certain types of motion, may lead to further refinement of automatic detection procedures. Bussmann, Veltink, Martens and Stam (1994), who conducted a similar study, made use of video analysis to record the actual behavior. We preferred behavior observation by a participant observer instead. Video analysis is time-consuming and the video recording itself may produce unwanted variance because of irritation and social interaction when performed outside the laboratory.

2. Materials and methods

2.1. Participants

In this study, 24 male university students (age range = 21–34 years, $M = 26$ years) served as paid voluntary participants. The participants were told that the study would investigate various measures to assess physical activity. Informed consent was obtained.

2.2. Apparatus

The Vitaport 2 (Vitaport EDV Systeme GmbH, Erftstadt, Germany) was used for the multichannel recording. Vitaport 2 is a general purpose digital recorder/analyzer (32 bit microprocessor, 16 MHz) with minimized dimensions and power consumption designed for prolonged ambulatory recording. It weighs 700 g. The recorder is carried in a padded bag worn on a belt at the waist. The universal module includes eight analog input channels (16 kHz at 12 bit A/D), with software programmable amplifier gain, high and low pass filter. Storage is available on 16 MByte RAM and 131 MByte Disk. The postprocessing is carried out on Vitagraph Software or add-on analysis programs developed by the user (Jain et al., 1996).

2.3. Accelerometry

The four sensors (IC Sensor Model 3031) were piezoresistive, light-weight, had wide bandwidth (i.e. DC and AC response), high sensitivity $\sim$1 mV/g (standard range $\pm$2 g), a typical accuracy of $\pm$0.2%, and the frequency response was practically linear up to the kHz range. The sensors (supplied by Vitaport, Becker Ingenieurbüro, Karlsruhe, Germany), were mounted, 20×20×2 mm, weight 4 g, and were equipped by the manufacturer with offset compensation and temperature drift compensation.

The sensors were calibrated by measuring the signal under controlled inclination, i.e. by rotating the sensor providing a signal output corresponding to +1 and −1 $\boldsymbol{g}$ (the gravitational constant). The DC output is zero when the sensitive axis is parallel to the gravitational axis. The recordings were obtained with a 16 Hz sampling rate and low pass filtering at 12 Hz. A higher sampling rate was both unnecessary, and given the limited storage and battery power, undesirable.

Four sensors were used:

1. sternum: the sensor that had previously been placed at the regio infraclavicularis was now placed at the sternum about 5 cm below the jugulum, in order to reduce side effects caused by arm movements;

2. wrist (preferred hand): dorsum of the wrist distal from the m. extensor carpi ulnaris;
3. thigh (preferred leg): frontal aspect of thigh, distal from m. rectus femoris; and
4. lower leg (preferred leg): frontal aspect of the tibia about 15 cm distal from the patella.

The sensors were fastened with Velcro bands, and the flexible cables were fixed to the skin with adhesive medical tape. All connections lead centripetally to the trunk (Vitaport recorder). The sensitive axis of the sensors was roughly perpendicular to the surface, i.e. to the frontal aspect of the sternum, dorsum of the lower arm segment, frontal aspect of thigh, and lower leg segment.

Two further channels, vertical movement of the head and speech activity, were included to explore the potential advantages of such measures. A sensor was fastened between left ear and mastoid to detect vertical movements of the head. A small throat micro (condenser microphone, Rimkus Medizintechnik, Riemerling, Germany) was fixed at the left aspect of the larynx. The output was amplified and filtered (HP 300 Hz, LP 1000 Hz), and rectified and smoothed (time constant = 7 ms). Heart rate was obtained by an electrocardiogram from modified Nehb anterior leads.

2.4. Procedure

After electrodes and sensors were attached and checked, the following conditions were carried out in a fixed order:

1. sitting (duration 60 s);
2. standing (duration 60 s);
3. lying supine (duration 60 s);
4. sitting and talking (duration 60 s);
5. sitting and operating PC keyboard (duration 60 s);
6. walking (duration 60 s);
7. stairs up (duration about 40 s); participants were asked to climb stairs (60 steps) at their usual speed in the laboratory building;
8. stairs down (duration about 40 s); and
9. cycling (duration about 40 s); participants rode a bicycle around the block.

The record was obtained twice, at the beginning of the recordings and after returning to the laboratory. The participants (and the participant observer, M.S.) spent about 50 min outside the laboratory and engaged in various activities, whereby the observer suggested some kinds of activities in order to obtain a wide range of postures and motions, e.g. upstairs, downstairs, sitting, and lying. However, the participants were relatively free to choose certain settings, e.g. coffee shop, cafeteria, library, reading a newspaper, conversation, etc. Behaviors were recorded as precisely as possible using a prepared form and stop-watch. A time resolution of at least 3 s was achieved throughout and a segmentation was provided according to the behavior observation, without knowledge of the kinematic analyses.

3. Data analysis

DC and AC components of the raw signal were separated by means of a digitally simulated resistance-capacitance circuit, corresponding to conventional analog filtering, with a cut-off frequency at 0.5 Hz (3 dB). DC- and AC-values were averaged across data points for each condition and monitoring segment (cf. Fahrenberg et al., 1997). Each ambulatory monitoring segment of at least 20 s duration was classified and stored together with the observed activity noted by the participant observer.

Monitoring data segments were classified by referring to the standard protocol variable profiles. Similarity is determined by the so called L_1 distances (e.g. Halmos, 1950). The L_1 distance between two conditions j and k with the variables $i = 1 \ldots \mathrm{nv}$ is defined as:

$$\delta_{jk} = \Sigma_{i=1\ldots\mathrm{nv}} \mid x_{ij} - x_{ik} \mid . \tag{1}$$

Different to the L_2 distance (Euclidian Distance) $\sqrt{\Sigma_{i=1\ldots\mathrm{nv}}(x_{ij} - x_{ik})^2}$ which makes an adjustment for the risk of variables with large differences, in L_1 distance large and small differences are treated equally.

Whenever the variables used have different scalings (e.g. heart rate or acceleration) they have to be standardized. The most common standardization factor is the standard deviation as used, for example, for the z-transformation. In our investigation, however, we used a standardization factor which is suitable for the L_1 distance, namely the average absolute differences between the standard protocol conditions: for variable i we formulate:

$$\mathrm{s}_i = \Sigma_{j=1\ldots\mathrm{nc}}\Sigma_{k<j} \mid x_{ij} - x_{ik} \mid /[\mathrm{nc}(\mathrm{nc}-1)/2]. \tag{2}$$

This factor is a measure of discrimination of variable i between the ns standard protocol conditions. The standardized L_1 distance, therefore, is given by:

$$\mathrm{d}_{jk} = \Sigma_{i=1\ldots\mathrm{nv}} \mid x_{ij} - x_{ik} \mid /\mathrm{s}_i. \tag{3}$$

We can say that each of the standard protocol conditions represent a point in the nv-dimensional space given by the *nv* variables. A certain monitoring data segment m was labeled according to the standard protocol condition j to which it was nearest, i.e. whose L_1 distance d_{jm} was the smallest under the nc standard protocol conditions.

Recordings from sensor placements at the sternum, wrist, thigh, and lower leg (DC and AC components) as well as speech activity (AC component) were used for classifications. DC components were weighted by a factor of 2 to account for the substantial contribution of posture in detecting various motions.

The reliability of accelerometry was examined regarding (1) the retest reliability of the individual measures and (2) the retest reliability of the classification. The first and the second trial of the standard protocol were used and the percentage of correct classifications for the 24 participants×nine conditions was noted.

4. Results

Concerning the accelerometer DC and AC components and throat micro raw signal, substantial differences exist—according to the type of physical activity—between conditions. Retest reliabilities of individual measures differ in size. About 60% of the accelerometer DC and AC variables attain r_{tt} in the range of 0.80–0.99. The reliabilities for certain conditions were obviously dependent on the amount of variance present. For example, during walking the DC components (posture) sternum, wrist, thigh, lower leg, and head had different r_{tt} values 0.95, 0.41, 0.69, 0.95, and 0.97, respectively, compared to the same components during sitting, 0.73, 0.33, 0.66, 0.29, and 0.94, respectively; the reliabilities for corresponding AC components were 0.99, 0.96, 0.98, 0.98, and 0.98, respectively, during walking and 0.62, 0.25, 0.43, 0.67, and 0.50, respectively, during sitting.

The automatic detection of posture and motion was highly reliable when the method was applied to the recordings obtained for the nine conditions of the second standard protocol. There were only 4.2% misclassifications (nine out of 216; see Table 1). These misclassifications occurred because of an insufficient discrimination between walking and walking downstairs (five cases), between the three sitting conditions (three cases), and between walking and walking upstairs (one case).

A comparison of the means of the conditions between the first and second trial revealed highly significant differences ($p < 0.01$). These were mainly found in the AC components during walking and walking downstairs and, concerning each of the five sensor positions, in a higher level of activity during the second trial. This finding may indicate that participants increased speed of movement toward the end of the recording session, although the t-tests for dependent measures applied here were problematic in some instances on account of small variances.

In the case of ambulatory monitoring, the automatic detection of posture and motion was based on a total of 466 segments with a duration of 20 s or more. Incorrectly classified segments were observed in 155, i.e. 33% of segments (Table 1).

The cross-classification of observed and automatically detected posture and movements indicated that the discrimination between walking and walking downstairs and between the three conditions of sitting, sitting and talking, and sitting and operating the PC keyboard (Table 2) was especially difficult. Accordingly, the set of the observed conditions was reduced to five classes instead of the intended nine. When this classification was applied, the percentage of incorrectly detected postures and movements fell: 21 out of 466 (4.5%); however, it became evident that this result was mainly due to three participants (Nos. 9, 10, and 24).

Further analyses of discrepancies revealed that elimination of segments shorter than 40 s decreased the percentage of incorrectly classified segments to 69 out of 362

Table 1
Detection of posture and motion by accelerometry[a]

Participant	Standard protocol	Monitoring outside laboratory		
	Number of incorrectly classified (out of nine) in second trial	Total number of segments	Incorrectly classified relating to	
			Nine patterns	Five patterns
1	0	12	5	0
2	0	16	7	0
3	0	16	6	0
4	1	17	3	1
5	1	15	3	2
6	1	15	11	2
7	0	20	10	0
8	0	26	8	1
9	0	13	6	4
10	2	17	6	3
11	0	21	2	0
12	1	22	11	1
13	0	11	2	1
14	0	21	11	1
15	0	24	8	1
16	0	22	1	0
17	0	20	6	0
18	0	24	1	0
19	1	23	10	0
20	1	29	15	0
21	0	20	3	1
22	0	19	2	0
23	0	23	5	0
24	1	20	13	3
Total	9 (4.2%)	466	155 (33.3%)	21 (4.5%)

[a] The standard protocol comprises nine conditions: sitting, standing, lying, sitting/talking, sitting/operating PC, walking, stairs up, stairs down, cycling. These patterns were used as a reference in detection of posture and motion in daily activities. The number of incorrectly classified segments were denoted referring to these nine patterns and, also referring to a reduced set of five classes whereby sitting, sitting/talking and sitting/operating keyboard were grouped together and walking/upstairs/downstairs as well.

(19%). The reduction from nine to five classes (discussed earlier) led to 17 (4.7%) misclassifications.

5. Discussion

The previous investigation (Fahrenberg et al., 1997) showed that the new methodology, which was based on calibrated sensors, AC/DC-division of the accelerometer signal, and on a stepwise discriminatory analysis of recordings,

Table 2
Cross-classification of observed and detected postures and motions ($n = 24$)[a]

Detected	Observed									
	Lying	Sitting	Sitting/talking	Sitting/operating	Standing	Walking	Walking/downstairs	Walking/upstairs	Cycling	Total
Lying	16	0	0	0	0	0	0	0	0	16
Sitting	2	**6**	**2**	**0**	2	0	0	0	0	12
Sitting/talking	0	**3**	**2**	**0**	1	0	0	0	0	6
Sitting/operating	0	**16**	**3**	**2**	1	0	0	0	0	22
Standing	0	0	0	0	114	3	1	0	0	118
Walking	0	0	0	0	6	**107**	**4**	**4**	0	121
Walking/downstairs	0	0	0	0	2	**80**	**26**	**1**	0	108
Walking/upstairs	0	0	0	0	3	**20**	**1**	**25**	0	49
Cycling	0	0	0	0	0	0	0	0	13	13
Total	18	25	7	2	129	210	32	30	13	466

[a] The results in bold indicate two classes of similar motions where the consistency is less satisfactory.

proved successful in detecting posture and motions for laboratory-based recordings. The protocol consisted of a standardized sequence of physical activities, although the participants' pattern of movement was not restricted. Once again, the findings obtained in the present investigation show a high retest reliability.

As expected, it was more difficult to detect postures and motions during ambulatory monitoring outside the laboratory building, where behavior observation was carried out in order to obtain an objective reference. The strategy for detecting behaviors used DC and AC components from four sensors and speech activity, and incorporated standardization and weights. This strategy was satisfactory for the majority of participants and conditions. The percentage of correctly classified segments increased from 67 to 81% when segments with a duration of at least 40 s were analyzed. However, in the case of a number of participants, the discrimination of the three conditions of sitting and the conditions of walking downstairs and walking was particularly unreliable.

Speech activity, although a promising parameter in behavior assessment, appeared to be less valid in the present study. The evaluation of the speech parameter was affected by the distribution of activities: the condition 'sitting and talking' was less often observed than expected and talking also occurred during other conditions. It is evident from the raw signal means of speech activity that this channel would be useful in discriminating between 'sitting and talking' (mean 10.45 μVolt) 'sitting' (mean 0.15 μVolt) and 'sitting and operating PC keyboard' (mean 0.31 μVolt). However, since speech activity was not a continuous signal, the averaging across segments should be replaced by more appropriate techniques of data analysis.

The classification can be improved by lengthening segments and reducing the behavioral classes to five. This finding may raise the question as to which segment length and which types of different motor behavior would actually be reasonable. It would appear to early to give a general conclusion. The time resolution and selection of behavior category will depend on the purpose of the investigation and on the dynamics of the actual behavior.

An investigation using a basically similar methodology was published by Bussmann et al. (1994). Recordings from four healthy participants and four amputees followed a protocol that included lying, standing, sitting, and dynamic conditions (i.e. a number of functional activities in a semi-natural setting). The correlation between video analysis and accelerometry, which used two sensors at the sternum, perpendicular to each other for tangential and radial direction, and one sensor placed at the upper leg, was reported to be high: range of 80–99% for postures and 73% for dynamic activity.

It may also be concluded from the present investigation that this methodology is suited to the detection of a variety of motion patterns in the natural setting, provided that the individual's basic patterns are previously assessed under laboratory conditions as a reference. The choice of these tasks is therefore a crucial aspect. The selection used here covered a very large range of postures and movements in daily life. However, it cannot give a complete description because specific or mixed behaviors may occur. The outcome of the present validation study encourages the further development of this methodology. A behavior protocol based on multi-channel recordings and data reduction using the methodology developed here is depicted in Fig. 1.

There are several aspects where methodological refinement may be achieved. These are the use of biaxial or triaxial instead of uniaxial sensors and the selection of sensor placements that are, perhaps, more suitable; these refinements may assist in achieving comparable results with only three channels. Another suggestion would be the registration of further channels. In the present study, a more reliable discrimination between walking and walking downstairs could have been attained by the inclusion of heart rate as a predictor. The average heart rates (standard protocol) were 89 and 103 bpm for the task of walking and walking downstairs.

Inspection of certain discrepancies between observed and detected conditions revealed a number of issues that may hopefully be resolved by further methodological refinement. Some participants obviously behaved less naturally under laboratory conditions, exhibiting, for example, somewhat restricted movement during the laboratory test of walking as compared to free movement outside. On the other hand, lying supine under the field condition was more variable than in the laboratory. The DC components from thigh and lower leg of some participants indicated that the legs were not in a horizontal position. Accordingly, the discrimination

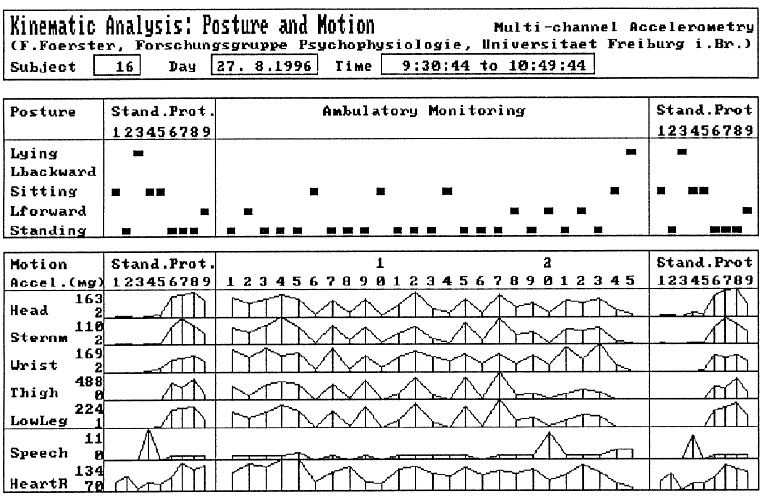

Fig. 1. Kinematic analysis of posture and motion based on calibrated accelerometry for Participant No. 16. The standard protocol (left-side) consisting of nine conditions was repeated once (right-side). In ambulatory monitoring, 30 segments (duration >20 s) were obtained. Accelerometer recordings from sternum, wrist, thigh, and lower leg, were used for classification of posture and motions. The heavy dashes in the upper section represent change in posture and the polygons in the lower section indicate amount of physical activity (mg) and speech activity (relative units). Heart rate (bpm) was also included in this protocol as an indirect measure of physical activity; however, heart rate was not used at this stage for classification of patterns.

between lying and sitting was more difficult. A few misclassifications of standing and walking were also noteworthy (Table 2); however, the reliability of the observation may be lower in some of these instances because segments were rather short in duration.

The present study seems to suggest that segments of 30 s might be a tentative compromise between resolution and reliability of assessment. It could be desirable to extend the standard protocol to include sitting in a forward and backward leaning position, and, optionally, lying on the back, left and right side.

Appropriate reservations should be made as to the generalizability of this methodology. Placement of sensors and selection of variables will basically depend on the question to be researched. A sensor placed at the dorsal aspect of the hand and two sensors attached to the sternum and thigh of, for example, patients with Parkinson's disease, may suffice to assess posture, motion, and, furthermore, tremor activity (Foerster & Smeja, 1999; van Someren et al., 1998). The methodology developed here appears to be suitable for a large range of applications because it can be adapted easily: a set of reference patterns is to be obtained for each individual and for each of the specific postures and motions which are relevant to the investigation.

In the present study, the observer defined the segment length and type of behavior. A 100% accuracy is assumed because of the unfeasibility of employing a second, independent observer to control for the reliability of this behavior protocol. However, the crucial question of validity is whether a truly automatic detection of the basic types of posture and motor activity can be attained without prior segmentation on the basis of behavior observation. Is it possible to substitute behavioral observation? The obvious advantages of accelerometry warrant further investigation of the validity and reliability of such assessments. A standardization of sensor placement and general guidelines for calibrated accelerometry are desirable.

It should be mentioned that a variety of clinical field and workplace applications using calibrated accelerometry can be conceived of. As Jain et al. (1996) and Veltink and van Lummel (1994) commented, accelerometer devices can be mounted at various segments of the body. A wide variety of practical applications is thus made possible, for example, analysis of gait and walking frequency, or the recording of body rotation and motility during sleep.

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