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Motion pattern and posture: Correctly assessed by calibrated accelerometers

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Basic motion patterns and posture can be distinguished by multichannel accelerometry, as recently shown. A refinement of this method appeared to be desirable to further increase its effectiveness, especially to distinguish walking and climbing stairs, and body rotation during sleep. Recordings were made of 31 subjects, according to a standard protocol comprising 13 motions and postures. This recording was repeated three times with appropriate permutation. Five uni-axial sensors and three sites of placement (sternum with three axes, right and left thigh) were selected. A hierarchical classification strategy used a standard protocol (i. e., individual reference patterns) to distinguish subtypes of moving behaviors and posture. The analysis method of the actometer signals reliably detected 13 different postural and activity conditions (only 3.2 % misclassifications). A minimum set of sensors can be found for a given application; for example, a two-sensor configuration would clearly suffice to differentiate between four basic classes (sitting, standing, lying, moving) in ambulatory monitoring.

The assessment of movement and posture, and, generally, the kinematic analysis of behavior, has greatly profited from the progress made in sensor technology and advanced methods in signal analysis. The conventional method made use of wrist-worn actometers, tilt-switch transducers, mechanical pedometers, piezoceramic sensors, and other electronic devices to register movements. Actometer devices are suitable for many applications, and actometers are less expensive than the infrared-light method of kinematic analysis, easier to apply than recordings of the electromyogram, and more convenient than videotape analysis. The measurement of activity in psychology and medicine was reviewed by Tryon (1991; see also H. Bussmann, 1998).

Recent progress in the assessment of movement and posture resulted from three developments: First, the wide bandwidth of new piezoresistive (e.g., ICSensor Model 3031, Analog Devices ADXL202) and piezocapacitive sensors have paved the way for the development of a new method with calibrated actometers. The DC signal output (i.e., signal output <0.5 Hz) allows the assessment of change in position in relation to the gravitational axis (i.e., inclination in degrees). The AC signal output >0.5 Hz in terms of the gravitation—that is, g (or milli-g)—represents acceleration along the sensitive axis of the device; second, the development of pocket-sized digital data recorders has especially facilitated multichannel ambulatory monitoring and the 24-h recording of activity in daily life (see Fahrenberg & Myrtek, 1996); third, the increases in computer capacity that have made advanced methods of signal analysis possible—for example, joint time (amplitude)–frequency analysis and specific methods of filtering (see, e.g., Qian & Chen, 1996)—have benefited behavior analysis, too. Software has been developed for automatic detection of motion patterns in multichannel recordings.

Multichannel Accelerometry

Multichannel (multisite) accelerometry with calibrated sensors is thus a very promising method, and researchers are becoming increasingly aware of the many advantages of this approach and of its potential fields of application in psychology and medicine (see H. Bussmann, 1998; Jain, Martens, Mutz, Weifl, & Stephan, 1996; Veltink & van Lummel, 1994). The actual posture and the pattern of motion (beyond the measurement of physical activity) basically provide a frame of reference for the evaluation of many behaviors, symptoms, and physiological changes. For example, the assessment of resting conditions versus walking or climbing stairs appears to be an essential aspect in the psychophysiological investigation of cardiovascular change and energy expenditure under naturalistic conditions (Tuomisto, Johnston, & Schmidt, 1996). Furthermore, the detection of body rotation (whether the subject is sleeping on the left or right side) may be important for a more precise evaluation of nightly blood pressure changes since blood pressure depends on the hydrostatic level (referring to the level of the heart). Unnoticed body rotation may thus introduce arbitrary changes in the order up to 20-mm Hg (Pickering, 1991).

Further examples for the application of this method would be the assessment of gait, stability of posture, movement disorders (see H. Bussmann, 1998; Veltink & van

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Lummel, 1994), and movement pathologies—for example, the quantification of amplitude, frequency, and occurrence time of tremor in Parkinson's disease and its relation to posture and motion (Foerster & Smeja, 1999; Smeja et al., 1999; van Someren et al., 1998).

Multichannel accelerometry was evaluated recently in a number of ambulatory monitoring studies. The evaluation indicated the importance of the following questions: (1) Which algorithms are suitable for the detection of motion patterns and posture, and which sensor placements would provide a minimal configuration to assess a broad spectrum of functional activities (Busser, 1994; Busser, Ott, van Lummel, Uiterwaal, & Blank, 1997; H. Bussmann, 1998; J. B. J. Bussmann, Tulen, van Herel, & Stam, 1998; J. B. J. Bussmann, Veltink, Martens, & Stam, 1994; Fahrenberg, Foerster, Müller, & Smeja, 1997; Fahrenberg, Müller, Foerster, & Smeja, 1996; Foerster, Smeja, & Fahrenberg, 1999; Kiani, Snijders, & Gelsema, 1997; van de Weijer, Smits, de Haan, & van Lummel, 1994)? (2) Which sensor placement is the best for the *prediction of general physical activity and energy expenditure* (Bouten, Verboeket-van de Venne, Westerterp, Verduin, & Janssen, 1996; Middelkoop, van Dam, Smilde-van den Doel, & van Dijk, 1997; Myrtek, Brügner, & Müller, 1996; Patterson et al., 1993; Richardson, Leon, Jacobs, Ainsworth, & Serfass, 1995; Tuomisto et al., 1996; Walker, Heslop, Plummer, Essex, & Chandler, 1997)?

With a few exceptions, the aforementioned studies refer to only a small number of motion patterns. It is obvious that in addition to standing, sitting, lying, walking, and climbing stairs, further behaviors should be included (J. B. J. Bussmann et al., 1998; Foerster et al., 1999). Subtypes of lying (i.e., lying on the right or left side, supine or with back supported, and a preferred position at sleep onset) are necessary to monitor bed rest and nightly body rotation. Samples of walking at normal and fast pace are preferable to test the discrimination between walking and climbing stairs. The majority of investigations have used only a few sensors. In some instances, it appears doubtful that such sensors were calibrated. Several studies did not explicitly refer to the DC component as an indication of posture (inclination) and seemed to be content with just the analysis of movement. In addition, the subject samples studied were always small. However, posture and motion patterns exhibit a remarkable interindividual variability. A larger number of subjects is required to investigate such effects.

The algorithm for the detection of posture and motion patterns is still a crucial aspect of accelerometry. Several suggestions have been made as to how to achieve an adequate data reduction and to differentiate between a variety of dynamic activities under investigation. The development of pattern recognition systems based on different strategies has been proposed. Such classifier systems could be designed by using statistical algorithms, conventional or fuzzy logic, or artificial neural networks (Kiani et al., 1997; Martens, 1994). However, only two approaches have been used to a great extent (J. B. J. Bussmann et al., 1998; Fahrenberg et al., 1997; Foerster et al., 1999).

1. In fixed-threshold classification, motion patterns (e.g., walking, climbing stairs, and cycling) are discriminated by applying a threshold to the signal of the thigh actometer. The threshold is derived from empirical studies and is used for all subjects. The discrimination between more classes of motion patterns requires a greater number of threshold values and appropriate normative studies. Substantial interindividual differences in static and dynamic behaviors clearly lead to misclassifications.

2. In reference-pattern-based classification, the detection of motion patterns could be improved if individual reference patterns for each postural and activity condition were obtained by an initial recording of the essential patterns under investigation. Relating to such a standard protocol, multivariate analyses and pattern similarity coefficients can be used for the detection and labeling of an actual segment—that is, a motion pattern with reference to the standard protocol (Fahrenberg et al., 1997; Foerster et al., 1999).

In view of these considerations, we suggest the use of a reference-pattern-based classification rather than a fixed-threshold classification whenever possible. The standard protocol takes less than a minute of recording time for each posture and motion. The protocol can be easily adapted to specific subsets of behaviors, and the strategy is highly flexible since certain reference patterns may be included after the conclusion of the monitoring if necessary. Further refinement of the reference-pattern-based classification might be achieved by a hierarchical strategy that classifies postures and, subsequently, uses reference patterns for the discrimination between subsets of dynamic activities.

Only two studies based on subject samples of sufficient size have actually evaluated the discriminatory efficacy of different sensor configurations (H. Bussmann, 1998; Fahrenberg et al., 1997; see also Veltink, Bussmann, de Vries, Martens, & van Lummel, 1996). The selection of a minimal configuration would be of practical interest.

In the present study, we aimed to describe and test a method for evaluating movement and posture that features a refined hierarchical classification of patterns. This refined methodology should reduce the percentage of misclassifications reported previously, especially with regard to the difficult discrimination between walking and climbing stairs (Foerster et al., 1999).

An extended standard protocol should contain static and dynamic behaviors that have not been accounted for previously, specifically, subsets of sitting posture (leaning forward and backward) and lying (body rotation and lying position, back supported and knees slightly bent). The measurement of body rotation required an additional sensor placed on the sternum, sensitive in the y-direction (transversal). A sensor for the z-direction (longitudinal) indicates lying independent of body rotation and should be useful for distinguishing between climbing stairs and walking. Lying prone was not included because the placement of the recording system and sensors is uncomfortable in this position. Of course, this position could also be observed if one wanted to.

Table 1
Axes and Planes

Axis	Terms	Direction With Reference to Gravitational Axis (Sternum Longitudinal)
1	sagittal anterioposterior ventral–dorsal (pointing forward)	x
2	transversal lateral mediolateral horizontal (toward the left)	y
3	longitudinal vertical craniocaudal longitudinal (pointing up)	z

Note—Positive direction means that a positive signal is obtained, when, for example, a three-axial sensor placed on the sternum of the standing subject indicates movement forward, toward the left, and up.

The increase in the number of sensors and axial representations of movements does raise the question about which sensor configuration suffices to detect the major classes of posture and motion correctly. The answer will depend partly on the actual selection of movements and functional activities, although the main classes of posture and a set of basic motion patterns may be regarded as core patterns. Which sensor placement gives the minimal configuration for detection of these core patterns? An extended configuration using a larger number of sensors may be able to detect essential subtypes of, for example, moving or lying in bed, and may therefore be preferable for a full 24-h recording.

Sensor Placement

A variety of sites have been used in actimetry and accelerometry. Some of these sites were selected arbitrarily, particularly at positions where actometer devices could be fastened easily (e.g., at the wrist or ankle). Other sites were preferred because they were conventionally used for recording the electromyogram from prominent muscles—for example, the flexor carpi ulnaris muscle (forearm) or the peroneus muscle (lower leg). The flat design of today's actometers permits the placement of sensors on many parts of the body, even on the distal phalanx of the finger. Terminology is inconsistent across laboratories (Table 1). We suggest the descriptive terms *sagittal* (x-direction), *transversal* (y-direction), and *longitudinal* (z-direction) instead of the anatomical terminology referring to the anterioposterior, mediolateral, and craniocaudal axes.

The present study is an extension of previous investigations. A reliable evaluation of this method and the derivation of especially valid sensor configurations has been sought using a comparatively large number of subjects, a standard protocol containing 13 conditions repeated three times, a five-sensor accelerometry, and the refined hierarchical classification. The aim of the study is to propose a standardization that will lend itself to many future research applications.

METHOD

Participants

In this study, 31 male university students (age range = 20–32 years, $M = 25.1$, $SD = 3.2$ 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.

Apparatus

The Vitaport 2 (Becker Ingenieurbüro, Karlsruhe, 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 and high and low pass filters. Storage is available on 16-MB RAM and 260- (or 170-) MB disks. The postprocessing is carried out on Vitagraph Software (Jain et al., 1996) or add-on analysis programs developed by the user.

Accelerometry

The sensors (IC Sensor Model 3031) were piezoresistive. They have wide bandwidth (i.e., DC and AC response), high sensitivity [~1 mV/g (standard range ±2 g)], and a typical accuracy of ±0.2%. The frequency response is practically linear up to the kHz range. The sensors (supplied by Vitaport) were mounted, 20 × 20 × 2 mm, and weighed 4 g.

Each sensor was calibrated for a specific Vitaport 2 amplifier channel by measuring the signal under controlled inclination—that is, by rotating the sensor providing a signal output corresponding to +1 g and −1 g (the gravitational constant) at 0° and 180°, respectively, to the gravitational axis. The DC output is zero when the sensitive axis is perpendicular to the gravitational axis. The recordings were obtained with a 32-Hz sampling rate and low pass filtering at 20 Hz.

The sensors were used as follows:

1. Sternum. Three uni-axial sensors were placed adjacently at the sternum about 5 cm below the jugulum, the sensitive axes pointing in a (1) longitudinal, (2) sagittal, and (3) transversal direction—that is, in the z-, x-, and y-direction, respectively.

2. Thigh. Frontal aspect of (4) right and (5) left thigh, distal from m. rectus femoris, about 5 cm above the patella, the sensitive axes of the sensors were roughly perpendicular to the surface, that is, to the frontal aspect of the sternum and the frontal aspect of the thigh.

The sensors were attached with adhesive medical tape (Fixomull Stretch, Beiersdorf AG, Hamburg). The flexible cables were also fixed to the skin. All connections led centripetally to the trunk (Vitaport recorder).

Procedure

After electrodes and sensors were attached and checked, the following standard protocol was carried out in a fixed order, each condition lasting for at least 40 sec:

Block A:

1. Sitting, upright, palms on thighs or on table top
2. Sitting, leaning forward about 20° from upright position
3. Sitting, leaning backward about −45° from upright position

Table 2
Permutation of Blocked Conditions

Subject	Standard	Repetition 1	Repetition 2	Repetition 3
10	ABCDEF	CFBDEA	DFCBEA	ECDBAF
10	ABCDEF	DFCBEA	ECDBAF	CFBDEA
11	ABCDEF	ECDBAF	CFBDEA	DFCBEA

Block B:

1. Standing with palms toward thighs

Block C:

1. Lying, left side, legs slightly bent, left hand under the head, right hand on thigh
2. Lying supine, legs and arms outstretched
3. Lying, right side, legs slightly bent, right hand under the head, left hand on thigh
4. Lying, back supported, knees flexed, soles placed flat on the bed

Block D:

1. Walking, at normal pace
2. Walking, at fast pace

Block E:

1. Stairs up once (60-step staircase, six landings)
2. Stairs down once (60-step staircase, six landings)

Block F:

1. Cycling (Ergometer 60 W), leaning forward, hands resting on handlebar

The standard protocol was the same for each subject. For each of the following three repetitions a permutation of Blocks A–F was conducted (Table 2).

Data Analysis

Filtering. DC and AC components of the raw signal were separated by means of a first-order FIR digital filter with a cutoff frequency at 0.5 Hz (3 dB). Raw signal DC values and rectified AC values were averaged across data points for each condition and monitoring segment. Walk frequency was calculated by means of short-time Fourier transform within the frequency band of 0.5 to 4 Hz using the *z*- (longitudinal) axis of the sternum sensor (Fahrenberg et al., 1997; Foerster et al., 1999; Qian & Chen, 1996).

Hierarchical classification of posture and motion patterns. Data segments were classified by referring to the standard protocol variable profiles. Similarity was determined by the so-called L_1 distances (see, e.g., Halmos, 1950). The L_1 distance between two conditions *j* and *k* with the variables *i* = 1 . . . *nv* is defined as

$$\text{dist}_{jk} = \textstyle\sum_{i=1\,...\,nv} |x_{ij} - x_{ik}|. \tag{1}$$

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

The variables have to be standardized whenever they have different scaling (e.g., AC and DC variables). 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 suitable for the L_1 distance, namely the average absolute differences between the *ns* standard protocol conditions; for variable *i* we formulated:

$$s_i = \sum_{j=1...ns} \sum_{k<j} \frac{|x_{ij} - x_{ik}|}{ns\frac{ns-1}{2}}. \tag{2}$$

This factor is a measure of discrimination of variable *i* between the *ns* standard protocol conditions (or a respective subset of them). Hence, the standardized L_1 distance is given by

$$d_{jk} = \sum_{i=1...nv} \frac{|x_{ij} - x_{ik}|}{s_i}. \tag{3}$$

Each of the standard protocol conditions represents a point in the *nv*-dimensional space given by the *nv* variables. A certain data segment *m* was labeled according to the standard protocol condition *j* to which it was nearest—that is, whose L_1 distance *djm* was the smallest under the *ns* standard protocol conditions.

Hierarchical classification was conducted with a SAS datastep macro using subsequent subsets of variables to discriminate subsets of conditions. Table 3 summarizes the steps denoting variables and standard protocol situations used.

After posture (lying, sitting, standing) and motion (yes/no) were determined on the basis of discrimination (Steps 1 and 2), lying was categorized in detail (Step 4), and, if the subject was in supine position, Step 5; sitting, Step 6; walking on the level and up stairs, Step 3, and, if walking was selected, Step 7; and, finally, bicycle, Step 8. This classification procedure was applied to the three sets of repeated behaviors, that is, 39 (3 × 13) conditions.

Besides the complete five-sensor configuration, a two-sensor strategy was explored, as a minimum strategy. Two sensors, sternum

Table 3
Hierarchical Classification

Step	Specification	Discrimination Between Conditions (No. Conditions)	Variables/Sensors Used	Standardization Necessary
1	Posture	Lying (4), sitting (3), standing	DC of 3 sternum, 2 thigh	no
2	Motion	All	AC of 3 sternum, 2 thigh	no
3	Stairs	Walking (2), stairs (2)	AC and raw signal of 2 sternum (sagittal, longitudinal), 2 thigh, walk frequency	yes
4	Lying	Lying (4)	DC of sternum transversal	no
5	Supine	Lying supine, lying supported	DC of sternum sagittal and longitudinal	no
6	Sitting	Sitting (3)	DC of sternum sagittal and longitudinal	no
7	Walking	Walking (2)	Walk frequency	no
8	Bicycle	Sitting forward, bicycle	AC of sternum sagittal, 2 thigh	no

Table 4
Comparison of True and Detected Motions and Postures (Five-Sensor Configuration)

	Detected by Accelerometry													
Condition	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
1 Sitting upright	77	3	12	–	–	–	–	–	–	–	–	–	–	92
2 Sitting, leaning forward	–	92	–	–	–	–	–	–	–	–	–	–	–	92
3 Sitting, leaning backward	–	–	91	–	–	–	–	1	–	–	–	–	–	92
4 Standing	–	–	–	91	–	–	–	–	–	–	–	1	–	92
5 Lying, left side	–	–	–	–	92	1	–	–	–	–	–	–	–	93
6 Lying supine	–	–	–	–	–	92	–	1	–	–	–	–	–	93
7 Lying, right side	–	–	–	–	1	–	92	–	–	–	–	–	–	93
8 Lying, supported, knees up	2	–	1	–	–	–	–	89	–	–	–	–	–	92
9 Walking, normal pace	–	–	–	1	–	–	–	–	89	1	–	1	–	92
10 Walking, fast pace	–	–	–	–	–	–	–	–	1	90	–	–	–	91
11 Upstairs	–	–	–	–	–	–	–	–	3	2	87	1	–	93
12 Downstairs	–	–	–	–	–	–	–	–	3	1	–	89	–	93
13 Cycling	–	1	–	–	–	–	–	–	–	–	–	–	91	92
Total	79	96	104	92	93	93	92	91	96	94	87	92	91	1,200

Note—The accelerometric data obtained for the 13 conditions of the standard protocol were used as an individual reference pattern for the classification of the subsequently conducted three permutations of these conditions (3 × 31 = 93 classifications for each condition, 9 missing data points). [Contingency table, $\chi^2(144, N = 31) = 13.47, p < .001$]. Cramer's $V = 0.97$.

z-direction and thigh x-direction, should suffice to distinguish general classes of postures and motions—that is, sitting, standing, lying, and moving, whereby subtypes of behaviors would be disregarded.

RESULTS

An almost perfect concordance was found between the behavior protocol in the laboratory and the classification based on calibrated accelerometry with a five-sensor configuration (Table 4). Chi-square [$\chi^2(144, N = 31) = 13.47$] and Cramer's coefficient (V = 0.97) were highly significant and substantial. The overall agreement was impaired by only 38 (3.2 %) misclassifications, most of which concerned the discrimination between sitting upright/leaning backward and the discrimination between dynamic activities, that is, walking and climbing stairs.

The findings obtained with the two-sensor configuration—that is, z-direction of the sternum sensor and x-direction of the right thigh—are shown in Table 5. Since the sternum sensor x-direction (sagittal) and the y-direction (transversal) were disregarded, subtypes of walking, sitting, and lying could not be distinguished. The agreement for classes of lying, standing, moving, and sitting was almost perfect, with only 1.3% misclassifications.

DISCUSSION

The findings indicate that the method based on calibrated actometers is effective in assessing motion and posture. There was a lower percentage of misclassifications than in Foerster et al. (1999). The present investigation was successful in distinguishing walking and climbing stairs and body rotation in lying position.

The increase in effectiveness of the assessment was probably due to refinements in the method. First of all, one more sensor was used, allowing a three-axial recording from the sternum placement. The four-sensor configuration used previously was sternum, wrist, thigh, and lower leg. Second, the method of classification (Table 3) was a hierarchical procedure instead of the previous strategy of simultaneously comparing patterns and selecting the reference pattern with the smallest distance to label a certain segment.

There were also essential differences in the study design. Previously, the effectiveness of accelerometric detection of behaviors was evaluated by behavior observation in the field (Foerster et al., 1999). The uneven distribution of naturally occurring behaviors over the contingency table may have impaired the conclusiveness of these findings. With this in mind, the present study was designed so that an equally distributed selection of behaviors in experimentally permutated order would be included.

It should be mentioned that a number of specific factors may affect the reliability of accelerometric assessments. The sensitive axis of the sensor in the x-direction should be perpendicular to the surface in order to provide reliable measurements, but the precise placement of a sensor—for example, on the frontal aspect of the lower leg—is rather difficult. Precise positioning would require the use of a

Table 5
True and Detected Motions and Postures
(Two-Sensor Configuration)

	Detected by Accelerometry				
Condition	Sitting	Standing	Lying	Moving	Total
Sitting	276	–	–	3	279
Standing	1	91	1	–	93
Lying	3	–	367	1	371
Moving	2	4	1	457	464
Total	282	95	369	461	1,207

Note—The accelerometric data obtained for the 13 conditions of the standard protocol were used as an individual reference pattern for the classification of the subsequently conducted three permutations of these conditions (1,207 classifications, 2 missing data points) [Contingency table, $\chi^2(9, N = 31) = 3{,}459.7, p < .001$]. Cramer's $V = 0.98$.

Table 6
Proposed Sensor Configuration for Standard Accelerometric Detection of Posture and Motion Patterns

No. Sensors	Placement	Direction of Axis	Suited for Detection of
2	Sternum,	z	Basic classes: sitting, standing
	right thigh	x	lying, and moving
			(pace and vigor of stride)
4*	As above, and		
	sternum,	x	Subtypes of sitting and moving
	left thigh	x	(walking, climbing stairs, cycling)
5	As above, and		
	sternum	y	Body rotation in bed

*Recommended for optimal discrimination.

somewhat cumbersome splint or small wedge to ensure the adequate fixation of the sensor. At other sites, such as the sternum, individual morphology may present difficulties for correct positioning. According to H. Bussmann (1998), the deviation from the geometric axis should not be greater than 15° (corresponding here to 0.26 g). However, the relative sensor sensitivity depends on the orientation of the sensor, and the cosine function of this relationship is at a minimum at 0° and 180° and at a maximum at 90° inclination. The placement of two sensors near to each other and with two perpendicular axes (x- and z-direction or x- and y-direction) could reduce the effect of a less precise placement because the two axes achieve maximum sensitivity at different phases of movement.

It should be noted that the precise placement of sensors is essential when thresholds are used for the classification of motion. A classification that is based on individual reference patterns appears to be less susceptible to such deviations in absolute threshold values. In any case, careful positioning and fixation are an essential aspect of this methodology.

The DC component of an actometer signal may be affected by temperature drift and in the long run by the aging of electronic components. However, within a 24-h monitoring period, the effect of these off-sets is rather small if a reference pattern classification based on the standard protocol is used.

Two essential issues still have to be discussed. Would a smaller number of sensors suffice to obtain the same classification? Which placements would be recommended?

Three sensor configurations are proposed on the basis of the present findings (Table 6). While a two-sensor configuration may suffice to assess the four basic classes of sitting, standing, lying, and moving, more sensors are required to distinguish subtypes of moving. This would require at least three sensors or, for increased reliability of discrimination, a four-sensor configuration. With a five-sensor configuration, 13 motion patterns and postures can be detected, as shown in the present study. The quantification of hand tremor, for example, or the kinematic analysis of hand and arm movement requires additional sensors on the dorsal aspect of the hand. According to the specific aims of an assessment, an adequate selection can therefore be made.

In the choice of the classification procedure, there are several arguments in favor of a hierarchical classification using individual reference patterns. This method appears to be especially appropriate for these assessments because of the large interindividual variability and the multivariate patterning of posture and motion.

In conclusion, the present findings on the valid detection of motion patterns and posture by calibrated accelerometry suggest a standardization of this method. The two key aspects in this refined method are the sensor configuration (sites of placement) and the classification procedure. There are several points in favor of a hierarchical classification using individual reference patterns.

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APPENDIX

Procedure

After electrodes and sensors were attached and checked, the following standard protocol was carried out in a fixed order, each condition lasting for at least 40 sec:

Block A

Sitting, upright, palms on thighs or on table top,

Sitting, leaning forward about 20° from upright position,

Sitting, leaning backward about −45° from upright position.

Block B

Standing with palms toward thighs.

Block C

Lying, left side, legs slightly bent, left hand under the head, right hand on thigh.

Lying supine, legs and arms outstretched.

Lying, right side, legs slightly bent, right hand under the head, left hand on thigh.

Lying, back supported, knees flexed, soles placed flatly on the bed.

Block D

Walking, at normal pace.

Walking, at fast pace.

Block E

Stairs up (60-step staircase, 6 landings).

Stairs down (60-step staircase, 6 landings).

Block F

Cycling (Ergometer 60 W), leaning forward, hands resting on handlebar.

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