Ambulatory Monitoring of Mobility-Related Activities: the Initial Phase of the Development of an Activity Monitor

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Introduction

In rehabilitation there is need for instruments that allow, reliable and valid statements to be formulated concerning a functional or D(isability) level (1-7). Such statements can assist the clinician in diagnosing, in deciding on the appropriate therapy, in evaluating the patients progress and in evaluating the effects of treatment (1,2,6,8-14). Furthermore, reliability and validity are a condition sine qua non for justified statements in research (15).

Physical activity, locomotion, mobility etc., are related to functional performance and disability. They, therefore, form an important field of attention within rehabilitation medicine (11, 1-19). At the Institute of Rehabilitation of Erasmus University Rotterdam there is interest in obtaining insight into a patients (in this case amputee’s) activity pattern. This concerns the activities a patient performs during the day, and the frequency of occurrence and the duration of these activities.

Some instruments measuring aspects of mobility and locomotion, such as observational techniques, have practical shortcomings, because they are time-consuming and difficult to interpret (1,12,20).

There are also a number of methodological problems (12, 21-24). Some instruments interfere with the subject’s performance. Other instruments, such as self assessment scales, diaries, questionnaires and clinical observation, are subjective (8,20,22,23, 32). Measurements within a laboratory or a physician’s room (e.g. assessment of gait) have limited validity, because the setting is highly artificial (2,13,14,25,26,2831). Most evaluation techniques in rehabilitation emphasize capability (what a patient can do) over brief time intervals (11,22). Furthermore, the relation ship between function parameters (impairment) and functional parameters (disability) Is complex and ambiguous (27, 33, 34). Measurement of impairment can not, therefore, be used to assess disability.

In general it can be said that most instruments are Insufficiently practical, sensitive, reliable and valid. These considerations have led to a closer study of the pro-sect of ambulatory monitoring in measuring mobility-related parameters in rehabilitation.

Ambulatory monitoring

Ambulatory monitoring enables measurements to be performed on persons, without being spacebound by instruments, cables etc. (11,22,25). Quantitative data are stored directly in a memory unit~ without the intervention of a patient, researcher or observer. Consequently the measurements are potentially objective, non-interruptive and non labour-intensive.

The concept of ambulatory monitoring does not say anything about the kind of data measured and stored. The input depends on the types of sensor used.

Ambulatory monitoring is used in various fields outside of rehabilitation. Examples are monitoring ECO (37), blood pressure (38), activity level or energy expenditure (39), activities of psychological interest (21) and postures and motions of the spine (35). The use of ambulatory monitoring of activities round surgical treatments is described by Stock et al. (36).

Ambulatory monitoring in rehabilitation

Van den Berg and van Asbeck (40) conducted long-term EMG measurements on 1 patient with a spinal cord lesion. Rozendal et al. (41) monitored heart frequency during standardized daily activities in a laboratory. Some studies are directed at walking and walking-related parameters (11,42,43). Halstead (11) described the monitoring of functional parameters like wheelchair mobility and time-out-of...

Summary: Long-term ambulatory monitoring of mobility-related activities is a method of collecting data that overcomes some of the shortcomings of most other methods in rehabilitation. The aim of the first phase project is the development of a user- and patient-friendly instrument that enables distinguishing between a Set of selected mobility-related activities in a reliable and valid manner. Accelerometers appear to be the most appropriate sensors to use. In this study a first set of mobility-related activities is formulated. The configuration of sensors and the analytical algorithms, which form the starting point for subsequent investigations, are determined. The set of selected activities consists of lying, sitting, standing, walking, walking up- and down stairs and cycling. The study demonstrates that the optimal configuration consists of 3 accelerometers, 2 on the trunk and 1 on the upper leg. With this configuration of sensors and using relatively simple analytical algorithms it is possible to distinguish the activities mentioned. It appears that the detection of static activities is less complex than the detection of dynamic activities. The reliability and validity of the instrument will be investigated in the next phase of the project.

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Holden and Fernie monitored ambulatory footsteps of amputees (44). Within the framework of the CAMARC project (Computer Aided Motion Analysis in a Rehabilitation Context) of the Commission of the European Communities, there also is interest in ambulatory monitoring (13, 45). The use of ambulatory monitoring within rehabilitation still is, however, relatively new. A few aspects of the current study are already described by Veltink et al. (46).

Ambulatory monitoring may be a means of overcoming the problems outlined earlier. The method can be directed at activities (disability) rather than at functions (Impairment). The nature of the instrument enables measurements in an natural setting during the normal activities of daily life. Information can, therefore, be obtained about what a patient is capable of doing, as well as about what a patient actually does (11,47). However, the reliability and validity of the method depends on the specific use to which it is put, and have to be investigated. The basic design of the instrument is shown in Figure 1. Because of the interest in the activities of a patient during an entire day, the measurements have to be performed for a minimum of 12 hours. Besides methodological requirements as reliability and validity, aspects of clinical use (1, 12,48) has been kept in mind in designing the instrument.

The aim of the first phase of the project, therefore, is the development of a user- and patient-friendly instrument by which a set of selected mobility-related activities can be measured over a long-term period and distinguished automatically in a reliable and valid manner. This instrument is called Activity Monitor.

The research questions are:
1. Which mobility-related activities have to be distinguished from each other?
2. Which sensor configuration and analytical algorithms can distinguish these activities?

Subjects and methods

Selections of the set of mobility-related activities

The choice of activities depends on a number of criteria:
- the activities have to be related to mobility;
- the set of activities has to cover all commonly occurring daily activities as much as possible;
- the set has to be of Limited size;
- the activities have to be relevant with regard to functional performance.

In order to create this set of activities several lines of investigations were pursued: a literature study primary directed at the assessment of (disability in) mobility and locomotion of amputees, consultations with rehabilitation specialists and physiotherapists, and interviews with patients who have had a (partial) leg amputation.

Benson

To discriminate between a number of activities, several types of sensors can be used. In this study uni-axial, piezo-resistive accelerometers (IC model 3031, t 5 g) are used (48). This choice is for a number of reasons.

The acceleration signal produced by a piezo-resistive accelerometer is the result of the current dynamic- acceleration and the vertical gravitational force; the signal depends on the orientation of the accelerometer relative to the gravitational force and the direction of the acceleration. In the case of static activities, when no accelerations occur, the value of the signal will range from - 1 g to +1 g (*9.81 m/s², Figure 2). Besides their ability to reflect dynamic and static ac-
sensors was determined empirically. The sensitive axis of the sensors was in the tangential or radial direction (Fig. 3). The duration of each measurement was approximately 20 to 30 min. The acceleration signals were amplified. A-D converted at 100 Hz and stored in a portable data recorder (Vitaport™ System). The recorder was carried on a belt around the pelvis.

A video recording was made simultaneously. Synchronization is achieved by synchronization markers on a marker channel of the data recorder and on the video recording. The definition of the sample settings and the transfer of the data to the computer was performed by means of the Vitagraph™ software. Several forms of data processing were applied, such as high pass and low pass filters, rectify procedures, averaging, and frequency analysis, to determine the optimal configuration and analytical algorithms. For signal analysis S.P.I.L.™ (Signal Processing and Inferencing Language) was used.

Results
Selection of a set of mobility-related activities
The following activities were selected: lying, standing, sitting, walking, walking upstairs, walking downstairs, and cycling.

Development of the sensor configuration and the analytical algorithms
After the selection of the set of activities a decision scheme was created (Fig. 4). This basic scheme was then used to structure the method of analysis.

Static versus dynamic activities
Dynamic activities differ from static activities by the occurrence of acceleration signals that rapidly change with time. By the subsequent use of a high-pass filter, a rectifying procedure, a low-pass filter and the application of a threshold, it is possible to distinguish dynamic activities from static activities (Fig. 5).

Static activities
Table 2 represents the theoretical values of the signals of 4 accelerometers attached to the trunk and to the right upper leg, during several static activities. During the actual performance of static activities, the signals will only come close to these values, due to deviations from the exactly ver

Development of the sensor configuration and the analytical algorithms
A number of demands is put on the sensor configuration and the algorithms:
- the number of sensors has to be as small as possible;
- the sensors have to be attached to the skin as close as possible to the recorder;
- the measurement technique must not significantly influence the performance of the evaluated activity;
- the instrument have to be sensitive, reliable and valid.

On theoretical grounds it is possible to create a configuration, which allows a number of static activities to be distinguished. However, the same is not possible for dynamic activities. For this reason measurements were performed.

Measurements and Instrument
On the basis of the set of mobility-related activities a protocol was drawn up. 5 healthy male subjects had to perform a number of activities, most of them in a number of different ways (Table 1). 5 accelerometers were attached to the skin with double-sided tape. The optimum location of the

![Fig. 4. The decision scheme for distinguishing the selected mobility-related activities.](image-url)
tical and horizontal position of the sensors and body segments. Note that 3 sensors are necessary to discriminate the static activities. The combination of 1 accelerometer in the tangential direction on the upper leg and 2 accelerometers (in tangential and radial directions) on the trunk results in unique combinations. This configuration also enables to distinguish different forms of lying. The signals of 3 accelerometers during the static activities, the output for the "Static/Dynamic" procedure and the output for the Select static activities" procedure are displayed in Figure 6.

**Cyclic versus non-cyclic activities**

In contrast to non-cyclic activities, the acceleration signals of cyclic activities consist of patterns that are repeated during a certain period of time. The shape, time or frequency characteristics of such patterns can be used to discriminate between cyclic and non-cyclic activities. Examples of dynamic, non-cyclic activities are the transitions between a number of static activities (Figure 6).

**Cyclic activities**

Figures 7 and 8 show 2 accelerometer signals for a single subject during dynamic, cyclic activities such as walking, walking up stairs and walking down stairs. Figure 9 represents the signals for cycling.

The patterns for walking, walking up stairs and walking down stairs are rather similar. A possible point of difference, to be seen in Figures 7 and 8, is the mean value of the signal during an activity. During walking up and down stairs the mean value of the signal from the tangential accelerometer on the upper leg is more positive than during walking. This can be explained by the fact that when walking stairs the upper leg is more raised on average than during walking on a level surface. The same principle can be used to discriminate between walking up stairs and walking down stairs: the mean of the signal from the tangential accelerometer on the trunk is more negative while walking up stairs, while when walking up stairs the trunk is more inclined on average than when walking down stairs. Cycling is relatively easy to distinguish from the other cyclic activities. The signals from the accelerometers on the trunk are not cyclic, in contrast to the signals from the sensors on the upper leg.

**Discussion**

**Set of static and dynamic activities**

Several criteria play a role in creating a set of mobility-related activities. The set does not cover all possible static and dynamic activities. A relevant extension of the list is already implicitly possible: the transition phases between the activities of the set, such as standing up and sitting down.

One might consider cycling as being a non-important activity. In The Netherlands, however, cycling is an important method of transport and often forms a rehabilitation goal for patients. Amputees will form the first target group of the research. Because they may use a wheelchair, adding driving a wheelchair will extend the list of activities.

**Sensor configuration and analytical algorithms**

Dynamic and static activities are relatively simple to distinguish. The dynamic activities all include motions of the upper leg: the signal from the sensor at the upper leg is, there-
fore, the most appropriate for distinguishing between static and dynamic activities. The classification of portions of the signal as representing a static or a dynamic activity depends strongly on the threshold chosen. Short-lasting (e.g. <2 s) dynamic activities can be regarded not being a dynamic activity; this can be implemented in the software. The choice of the location and the sensitive direction of the sensors is limited (Table 2). The accelerometers attached to the lower leg are of no use during static activities and have the disadvantage of long wires, which cross joints to the data recorder.

There are some reasons why a configuration of 3 accelerometers (with 1 tangential accelerometer on the upper leg and a tangential and a radial accelerometer on the trunk) is most desirable. Firstly, using only 2 accelerometers always results in 1 or more combinations that represent 2 or more static activities (Table 2). Secondly, due to the shape of the accelerometers attachment at the leg in the radial direction should be avoided. At last, the signals from measurements in a tangential direction are more valuable for distinguishing the cyclical activities (Fig. 7 and 8): tangential accelerometers are more sensitive to small changes in inclination while standing and walking.

The radial sensors of the trunk were located on the shoulder. Analytical problems did not occur, during this investigation but seem possible, because of the interfering effect of movement of the shoulder girdle. The attachment of the radial sensor on the sternum will be investigated.

Theoretically, 3 accelerometers are sufficient to distinguish the static activities. This configuration is also potentially adequate for differentiating the dynamic activities. For greater reliability, an extra accelerometer (e.g. on the other leg) may be useful. Such a configuration still meets the formulated requirements about the number and location of sensors.

The reliability and validity of the results of the Activity Monitor depends on the sensitivity and robustness of the analytical algorithms and quality of the input signals. The algorithms necessary to discriminate the 4 cyclic activities are more complex than the algorithms needed to distinguish static from dynamic activities or the algorithms to discriminate the 3 static activities. The quality of the input is strongly influenced by the orientation of the sensors: fixation onto the skin has to be done with care.

At this time the reliability and validity of the results of the Activity Monitor still needs further study, because the sensor configuration and the algorithms are based on the data for 5 young, healthy male subjects and the subjects performed fixed activities according to a set protocol. The data resulting from the measurements are used to develop the analytical algorithms. Therefore, the data can not be used to investigate the validity of the instrument.

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Future developments and applications

The next phase of the project will be directed at evaluating the reliability and validity of the results of this Activity Monitor. The setting and the activities will be less standardized and less artificial. Healthy subjects as well as amputees will be involved.

As described in the introduction, the primary goal of the Activity Monitor is to measure mobility-related activities over a full day period. The output of the instrument can be a histogram representing the total duration of each activity, a histogram representing the frequency of each activity and information about the mean, standard deviation and range of the duration of each activity. This type of information will be relevant in the clinical setting as well as in descriptive and evaluative studies. Duration and frequency of activities are not the only relevant aspects of mobility. The way in which a patient performs the activities (like speed, symmetry and step frequency of walking) are also important. The prospects of ambulatory monitoring using accelerometers in measuring more qualitative aspects will be considered.

References

(27) Lankhorst GJ: Assessment of functional abilities. Amsterdam, Amsterdam University, 1986, pp 62 (Diss.).
(35) Snijders CJ, Riel MP van, Nordin M: Continuous measurements of spine movements In normal working situations over periods of 8 hours or more. Ergonomics 1987:30:63-653.