4 Technical description of the Upper Limb - Activity Monitor

Partly based on:

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4.1 Abstract

Due to developments in data recording and sensor technology, advanced ambulatory systems that measure aspects of human functioning and behaviour during everyday life have become available. One such instrument is the Upper Limb-Activity Monitor (ULAM). This chapter provides a technical description of the ULAM. The ULAM is an extended version of the Activity Monitor (AM); both instruments are based on ambulatory accelerometry and aim at assessing body postures and motions, and in case of the ULAM also activity of the upper limbs. Signals from body-fixed acceleration sensors are recorded for a period of at least 24 hours in a subject's home environment during everyday life and continuously stored in a digital portable recorder. During post-measurement analysis, body postures, body motions and upper limb activity are detected by means of custom-made software programs.

4.2 Background

Human behaviour can be regarded as a complex of physical activities: body postures, body motions, and transitions between postures. Measuring human behaviour is of major importance for fundamental and applied clinical research in a large number of disciplines. If unobtrusive, objective and valid measurements of a large and specific set of body postures and motions (i.e. mobility-related activities) during everyday life in a subject's personal environment are required, most of the available techniques, such as questionnaires, observations and diaries are inadequate [1]. Recent developments in data recording (small, portable and digital data logger systems with increased data processing and –storage capacities) and simultaneous developments in sensor technology (small, non-drifting and robust sensors), however, enabled objective measurements for longer periods during everyday life using ambulatory monitoring devices. Two of such devices are the Activity Monitor (AM) and the Upper Limb-Activity Monitor (ULAM) [2-8]. Both AM and ULAM consist of several body-fixed acceleration sensors connected to a recorder that is worn in a belt around the waist and aim at long-term (24 hours) assessment of physical activity during everyday life.

The primary goal of rehabilitation medicine, i.e. regaining and/or maintaining functionality by decreasing the consequences that a disease or disorder may have on everyday life, provided the rationale for development of the AM and ULAM. The AM can be used to determine whether a subject is lying, sitting or standing (body postures), walking, running, climbing stairs, cycling, driving a wheelchair or performing general (non-cyclic) movements (body motions), or the transitions between the different body postures. Measuring such body postures and motions allows assessment of activity limitations. Indicators for activity limitations are, for example, lying down or sitting the greater part of the day, or a low number of transitions between postures. Because the AM was insufficient to detect activity limitations that are characteristic of upper limb disorders, the possibilities of the AM were extended using additional accelerometers on the forearms which resulted in the ULAM [8]. The ULAM is based on the following definition of upper limb usage: active movement of (parts of) the upper limb(s) in relation to proximal parts, holding and leaning. Its key characteristic is combined measurement of mobility-related activities and upper limb activity of both upper limbs. Although we have published [8] on the ULAM´s feasibility to measure normal and limited upper limb usage through measurement of upper limb activity, a comprehensive technical description of the analysis scheme and software programs of the ULAM has not been provided.

4.3 Technical description of the ULAM

Piezo-resistive accelerometers

The ULAM consists of five (or six) ADXL202 piezo-resistive accelerometers (Analog Devices, Breda, the Netherlands, adapted by Temec Instruments, Kerkrade, the Netherlands). Piezo-resistive accelerometers consist of a mass, connected to a frame by beams, which can be represented by a damped spring (figure 4.1) [6, 9, 10]. Piezo-resistors are mounted in the beams and form a bridge circuit. The value of the resistors depends on the magnitude of acceleration. The raw acceleration signals yielded by the piezo-resistive accelerometers are a combination of the gravitational acceleration ($\bar{a}_{grav}$, 9.81 ms^{-2}) and a component of the inertial acceleration ($\bar{a}_{inert}$). The part of $\bar{a}_{grav}$ that is measured ($\bar{a}_{grav,\ sens}$) depends on the angle φ_2 between the sensitive axis of the sensor and $\bar{a}_{grav}$. The part of $\bar{a}_{inert}$ that is measured ($\bar{a}_{inert,\ sens}$) depends on the angle φ_1 between the sensitive axis of the sensor and $\bar{a}_{inert}$. Because the gravitational force acts on the mass and the inertial forces act on the frame of the sensor, $\bar{a}_{grav}$, and $\bar{a}_{inert}$ have opposite effects on the spring. Therefore, the raw signal ($\bar{a}_{sens}$) produced by the sensor at a certain moment (t) can be expressed as $\bar{a}_{sens}$ (t) = $\bar{a}_{inert,\ sens}$ (t) - $\bar{a}_{grav,sens}$ (t). Theoretically, a constant $\bar{a}_{sens}$ smaller than 9.81 ms^{-2} can be the result of either a constant $\bar{a}_{inert}$ or the result of $\bar{a}_{grav}$; this can not be determined with a single accelerometer. The occurrence of a constant $\bar{a}_{inert}$ of several seconds duration is unlikely during the performance of dynamic mobility-related activities or upper limb activity in everyday life, however. Therefore, it is assumed that the body part that the sensor is attached to is active when the raw accelerometer signal is time varying (i.e. body motions are performed or there is upper limb movement). In contrast, the body part that the sensor is attached to it inactive when the raw accelerometer signal is constant (i.e. a body positions are performed or there is no upper limb movement). Assuming angular deviations in one plane, from a constant raw signal the angle between the accelerometer axis and the gravity vector can be determined, which gives information about the orientation of the accelerometer [10, 11].

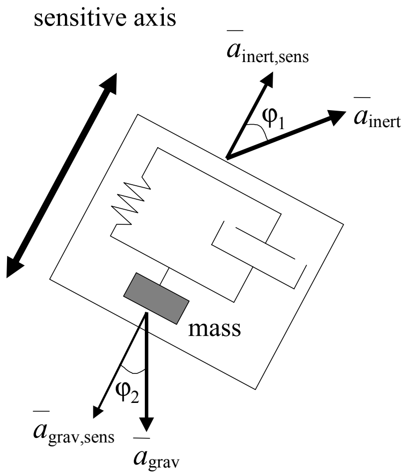


Figure 4.1: Scheme of a piezoresistive accelerometer. $\bar{a}_{grav,}$ gravitational acceleration; $\bar{a}_{inert.}$ inertial acceleration; $\bar{a}_{***sens,}$ the part of the gravitational or inertial acceleration measured by the accelerometer.

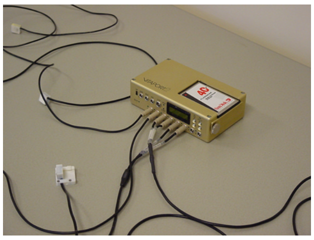
Measurement set-up

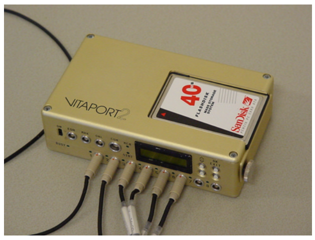
The acceleration sensors (size about 1.5x1.5x1.0 cm) are fixed on Rolian Kushionflex (Smith & Nephew, Hoofddorp, the Netherlands) or silicone based stickers (Schwa-Medico, Ehringshausen, Germany) by double-sided tape; both materials can be fixed directly on the skin. One sensor is attached at the lateral side of the thigh, at the level halfway between trochantor major and knee joint. A sensor on the other thigh is optional. The sensitive axis of this uni-axial sensor is in sagittal direction while the subject is in the anatomical position. A bi-axial (or two uni-axial) sensor(s) is (are) attached on the lower part of the sternum, with sensitive axes in the sagittal and longitudinal direction. These accelerometers have to be attached with their sensitive axis as parallel as possible to the related anatomical axis; for the thigh and trunk sensors a deviation of 15 degrees is allowed. If a sensor cannot be attached within this range, a wedge is used. For the ULAM two additional uni-axial sensors are attached to the forearms, just proximal from the wrist joint with the sensitive axis in the sagittal direction while the subject is in the anatomical position. It has to be noticed that sometimes concessions have to be made with respect to proximal-distal sensor attachment as a consequence of the upper limb disorder under investigation. An important aspect for the forearm sensors is identical placement on both upper limbs. Each accelerometer is attached to a data recorder by means of separate lemo-jackets. The recorder is worn in a belt around the waist and before measurements are started, the accelerometers are calibrated (+1g and –1g).

Recorder

The data recorder should allow measurements of at least 24 hours with respect to data storage and energy supply, be able to measure (at least) five accelerometer signals, have small dimensions and low weight, and be easy to handle by researchers and clinicians. For the ULAM, a Vitaport2™ (Temec Instruments) digital recorder (9x15x4.5 cm, 500 grams) with energy supplied by four penlite batteries was used (figure 4.2). The Vitaport2™ universal module allows simultaneous measurement of up to eight signals; data are stored on a flash card of 40 MB). Continuous measurement (without changing batteries or disks) of over three days is possible, but until now only 24-h measurements have been performed. The data recorder must contain a ´definition file´ representing the measurement set-up. The measurement set-up consists (among other things) of calibration and offset factors, sample frequency (32 Hz), resolution (12 bits) and filters (30 Hz low-pass). Signals are continuously measured and stored. After the measurements, the data are downloaded onto a PC for analysis.

Figure 4.2: The Vitaport2™ used for the application studies with the ULAM.





Signal analysis

After the measurements, detection of mobility-related activities and upper limb (in)activity takes place by means of proprietary ´signal processing and inferencing language´(SPIL), yielding C-code [12]. In this automatic analysis, several parts can be distinguished (figure 4.3).

1) The first part is feature extraction, which means that new signals (feature signals) with specific characteristics are derived and computed from each raw acceleration signal. For the trunk and thigh signals, three features (low pass (LP) /angular, motility and frequency) are derived, and for the forearm signals only the motility and LP/angular features are derived.

2) The second part of analysis of the trunk and thigh signals consists of body posture and motion detection, which means that body postures and body motions are classified on the basis of the feature signals from trunk and thigh sensors. In this part of the analysis also some post-processing takes place. The pattern of body postures and motions (also referred to as mobility-related activities) is the basis for the detection of upper limb (in)activity in the subsequent parts of data analysis.

3) Upper Limb Activity detection:

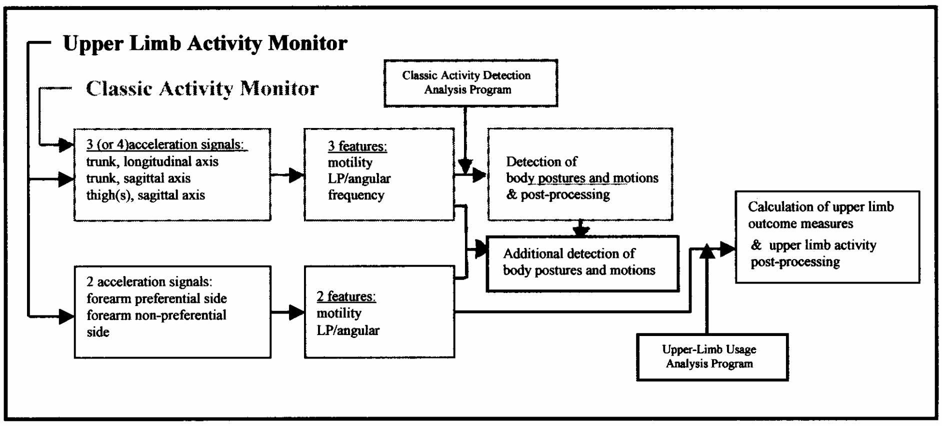
a) Additional body posture and motion detection using features from the signals of the forearms.

b) Based on information on body postures and motions and feature signal data from the forearms, a set of Upper Limb Activity measures are calculated.

c) Upper limb activity post-processing.

These subsequent parts will be described in the following paragraphs.

Figure 4.3: The Upper Limb-Activity Monitor and its analysis program in relation to the classic version of the Activity Monitor and its analysis program.



Feature extraction

The feature signals are continuously computed from each measured accelerometer signal (see also figures 3.3 chapter 3 and 5.1 chapter 5, this thesis). The *LP/angular feature* signals are created after low-pass filtering (finite impulse response filter, cut-off frequency 0.3 Hz). These signals are subsequently averaged over 1 second intervals and converted to angles via an arcsine transformation (range –90º to + 90º), although the translation to an angular position of the sensor is not straightforward (e.g. during motion and multidimensional angular positions). The *frequency feature* signals are based on a band-pass-filtered derivative (0.6-4 Hz for the trunk signals and 0.3-2 Hz for signals from other sites of attachment), also with the use of finite impulse response filters. This band-passed signal (which ideally has a sinusoid shape with the movement frequency of the segment the sensor is attached to) is the input of the fast time frequency transform (FTFT) procedure [13]. This procedure constitutes a particular type of instantaneous frequency analysis for signals and determines instantaneously the frequency and amplitude/envelope of the band-passed signal. To be regarded as valid, this raw instantaneous frequency must meet three criteria, pre-set in the so-called FTFT knowledge base: the frequency range, the amplitude (power) range of the band-pass-filtered signal, and the variability of the detected frequency. If the current signal does not meet all the pre-set criteria, no valid frequency is assigned; otherwise, the frequency is assigned to a frequency feature signal and averaged over 1 second intervals. The *motility feature* signals are created after subsequent filtering at 0.3-16 Hz and applying a root-mean-square (RMS) procedure during subsequent 1-second windows of filtered data; the RMS value is assigned to the motility feature signal (1Hz). This value depends on the variability of the measured signal around the mean.

Posture/motion detection

Based on the three feature signals derived from the measured trunk and thigh signals, more than 20 (sub) body postures and body motions are distinguished in the analysis program. For each subcategory and for each feature signal, a minimum and maximum value is a pre-set in the activity detection knowledge base. For consecutive intervals of 1 second, for each subcategory and for each feature signal, the ‘distance’ is calculated from the actual feature signal value to the pre-set range of feature signal values. Since the three features (LP/angular, frequency and motility) have different units (degrees, Hz and g, respectively), some features are scaled to allow a proportional influence of all features. If an actual feature signal value is within the pre-set range of a specific posture/motion subcategory, the calculated distance is zero – that is, it does not add to the total distance for that subcategory. The calculated distances of the feature signals are added for each subcategory; the body posture/motion with the lowest total distance in the end will be selected and detected. If a posture/motion is detected, but the distance is above a pre-set general threshold value, indicating a relatively high degree of unreliability, the category ‘unknown’ is selected.

There are some (optional) post-processing procedures after posture/motion detection. The first option is to reduce the number of categories from subcategories to main categories. Although most of the 23 subcategories are initially required to avoid misdetection, not all have to be of interest in a later phase, especially when subjects with an upper limb disorder are the topic of investigation. In our studies, the most often used main categories are the body postures lying, sitting and standing, including transitions, and the body motions walking, running, climbing stairs, cycling and general non-cyclic movements. A second post-processing option is applying duration thresholds, which means that postures/motions below certain duration are rejected because these may not be of clinical or methodological interest. In fact, each sample within a time window of n seconds around sample s is examined; the posture/motion that is most frequently detected in that window is assigned to sample s. The size of the frame determines the duration threshold (usually 5 seconds). Manual editing is the third option in post-processing. Although the validity of the AM is high, not all postures/motions are currently correctly detected (e.g. driving a car can only be determined by visual inspection at the moment, but it may be desirable to distinguish driving from sitting). In such situations, it is possible to manually correct or insert categories. If necessary, this type of manual post-processing has to be done before the SPIL routines for automatic detection of upper limb activity are applied in order to obtain unobtrusive information about upper limb (in)activity.

Detection of (limited) upper limb activity

As mentioned, the detection of upper limb (in)activity takes place after standard detection of mobility-related activities with the 'classic activity detection analysis program' (figure 4.3). The ULAM upper-limb usage analysis program consists of several sub-programs in which the SPIL-routines consisting of Boolean operators and pre-set motility thresholds are described [8, 12].

a) The first sub-program that is used generates additional body postures and motions (mobility-related activities) that were not yet detected with the classic activity detection analysis program. On the bases of the motility and LP/angular signals of the forearms and the average value of the trunk and thigh motility signals the following mobility-related activities are additionally detected: lying on the side undefined, lying on the right side, lying on the left side and sitting or standing during (public) transportation.

b) The second sub-program that is used performs the actual detection of upper limb activity and inactivity, for both upper limbs separately. For each forearm sensor, a new signal is generated that indicates per second whether there is upper limb activity or not; for each body posture and body motion, distinct pre-set thresholds were used for the motility signals of the forearm sensors in order to compensate for differences in general body movements due to postural sway or head movements during different mobility-related activities (see also [8]).

c) Post-processing in the 'upper limb usage analysis program' consists of creating statistics/reports. For each mobility-related activity an overview is provided of the number of samples (i.e. seconds) that the individual upper limbs were active or not. Also, the average motility value of the forearm sensors for each mobility-related activity can be obtained. The so-called ´report-files´ can be exported to Microsoft EXCEL to further calculate a large number of outcome measures (figure 4.4). The calculation of ULAM outcome measures may comprise the whole measurement period or one or more parts of it.

In the report files, some standard information is provided about the subject that was measured with the ULAM (part A, figure 4.4). Part B shows the number of walking, wheelchair (if applicable) or running periods of more than 10 seconds. Then in part C, an overview of transitions from one (coded) body position to another (coded) body position is provided. The number of transitions is also summed up, both for the total number of transitions and for the number of transitions with the transitions between different forms of lying excluded. Part D gives an overview of the duration (in seconds and in % of the measurement period) of each body posture and motion (i.e. mobility-related activity). Part E demonstrates the duration of upper limb activity and inactivity for both forearm sensors LaR and LaL separately for each of the body postures and motions. LaR refers to the involved upper limb when a patient is measured or to the dominant limb when a healthy subject is measured and LaL refers to the non-involved upper limb when a patient is measured or to the non-dominant limb when a healthy subject is measured. The bottom part (F) of the report shows the average motility values per acceleration sensor, for each body posture and motion separately. TruSag and TruLon refer to the sensor on the trunk with axes in the sagital and longitudinal direction. UlrSag refers to the sensor on the right upper leg with the axis in the sagital direction. MotBod is the average of summed motility values of the trunk and leg sensors. We would like to refer to the application studies described in this thesis (chapters 5-8) for a description of the ULAM outcome measures that were calculated from these report files and were actually used.

Figure 4.4: Example of a report file.

A

K I N E M A T I C - R E P O R T	
Subjects Last Name:	First name:
Date of birth:	Age:
Gender:	Subject ID:

B

WALKING PERIODS	
Walk Periods > 10s :	255
Wheelchair Periods > 10s :	0
Run Periods > 10s :	0

C

TRANSITIONS								
From/to	'10'	'20'	'30'	'40'	'50'	'60'	'70'	'00'
Lying back (10) :	0	10	0	5	0	0	0	0
Lying side (20) :	7	0	0	2	0	0	0	0
Lying prone (30) :	0	0	0	0	0	0	0	0
Standing (40) :	6	1	0	0	50	0	0	0
Sitting (50) :	0	0	0	50	0	0	0	0
Standing public trans (60) :	0	0	0	0	0	0	0	0
Sitting in car/public (70) :	0	0	0	0	0	0	0	0
Unknown (00) :	0	0	0	0	0	0	0	0
Number of transitions :	131							
# of transitions - lying :	114							

D

DURATION OF ACTIVITIES		
	Sec	%
Total duration (Sec.) :	86395	
Duration static activities:	72904	84.4
Duration dynamic " :	13491	15.6
Duration diverse " :	0	0.0
Lying back (10) :	22497	26.0
Lying side (20) :	18476	21.4
Lying prone (30) :	0	0.0
Standing (40) :	16972	19.6
Sitting (50) :	14959	17.3
Standing public trans(60) :	0	0.0
Sitting in car/public(70) :	0	0.0
Gen. movement (110) :	1807	2.1
Walking (120) :	11086	12.8
Climbing upstairs (130) :	0	0.0
Climbing downstairs (140) :	0	0.0
Driving wheelchair (150) :	0	0.0
Cycling (160) :	598	0.7
Running (170) :	0	0.0
Unknown (00) :	0	0.0

E

UPPER LIMB ACTIVITY	LaR inactive	LaR active	LaL inactive	LaL active
Lying back (10)	21878	619	21513	984
Lying side (20)	12366	297	12247	416
Lying side L (21)	3010	7	3011	6
Lying side R (22)	2785	11	2772	24
Lying prone (30)	0	0	0	0
Standing (40)	6401	10574	3725	13250
Sitting (50)	11358	3601	9675	5284
Standing PT (60)	0	0	0	0
Sitting PT (70)	0	0	0	0
Gen. movement (110)	128	1680	8	1800
Walking (120)	0	11086	0	11086
Climbing upstairs (130)	0	0	0	0
Climbing downstairs (140)	0	0	0	0
Driving wheelchair (150)	0	0	0	0
Cycling (160)	0	598	0	598
Running (170)	0	0	0	0

F

MOTILITIES versus ACTIVITIES						
Activity (code) :	MotBod	TruSag	TruLon	UlrSag	LaL	LaR
Lying back (10) :	0.0027	0.0019	0.0027	0.0030	0.0079	0.0050
Lying side (20) :	0.0023	0.0025	0.0019	0.0022	0.0046	0.0031
Lying prone (30) :	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Standing (40) :	0.0262	0.0275	0.0137	0.0317	0.1689	0.0617
Sitting (50) :	0.0060	0.0104	0.0052	0.0040	0.0515	0.0218
Gen. movement (110) :	0.0879	0.0969	0.0540	0.1004	0.2455	0.1097
Walking (120) :	0.1910	0.0925	0.1493	0.2612	0.1807	0.1300
Climbing upstairs (130) :	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Climbing downstairs (140) :	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Driving wheelchair (150) :	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cycling (160) :	0.1490	0.0390	0.0487	0.2541	0.0343	0.0861
Running (170) :	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Unknown (00) :						

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