3 Ambulatory measurement of upper limb usage and mobility-related activities during normal daily life with an Upper Limb-Activity Monitor: a feasibility study

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3.1 Abstract

Aim: To assess the ability of an Upper Limb-Activity Monitor (ULAM) to discriminate between upper limb usage and non-usage in healthy and disabled subjects during normal daily life. **Methods:** The ULAM was based on ambulatory accelerometry and consisted of several acceleration sensors connected to a small recorder worn around the waist. While wearing this ULAM, four healthy and four disabled subjects performed an activity protocol representing normal daily life upper limb usage or non-usage. The motility feature (derived from the raw acceleration signals) was used as a measure for the extent of upper limb usage. Agreement scores between ULAM output and videotape recordings (reference method) were calculated. **Results:** ULAM data that were of special interest for rehabilitation were detected satisfactorily (overall agreement 83.9%). There were no systematic differences in the agreement percentages between healthy and disabled subjects for mobility-related activities ($p=0.345$) and the different forms of upper limb usage or non-usage ($p=0.715$). **Conclusion:** It is considered feasible to use the ULAM in future studies in subjects with upper limb disorders to discriminate between upper limb usage and non-usage during performance of mobility-related activities in order to determine activity limitations.

3.2 Introduction

For many medical disciplines, and especially for rehabilitation medicine, instruments that focus on physical activities are of fundamental importance [1]. Instruments that objectively measure during normal daily life are essential to provide insight into activity limitations of patient groups. Until recently, reliable and valid instruments that objectively measure these activity limitations were lacking [2-4]. Therefore, an Activity Monitor (AM) based on ambulatory accelerometry was developed that consisted of acceleration sensors attached to the thighs and trunk, connected to a small recorder worn around the waist [5-9]. This device allows a number of mobility-related activities (such as lying, sitting, standing, walking, cycling and general movement) to be automatically detected for a period of 24-72 hours [10, 11]. Measurement of these activities allows the assessment of activity limitations. Indicators for these limitations are, for example, lying down or sitting the greater part of the day, or a low number of transitions between postures.

Activity limitations of subjects with disorders related to the upper limbs are not primarily expressed in mobility-related activities. Although these disorders can have some impact on the performance of mobility-related activities, the main limitations are those directly related to upper limb usage during normal daily life. The present configuration of the 'classic' AM, with sensors on thighs and trunk, is insufficient to measure upper limb usage. To make a statement about limited upper limb usage, valid measurement of 'normal' upper limb usage is a prerequisite. Therefore, it is necessary to adapt the 'classic' AM, which implies increasing the number of sensors and extending the analysis program. The aim of this study was to determine the feasibility of an Upper Limb-Activity Monitor (ULAM) to discriminate between (different forms of) upper limb usage and non-usage during normal daily life.

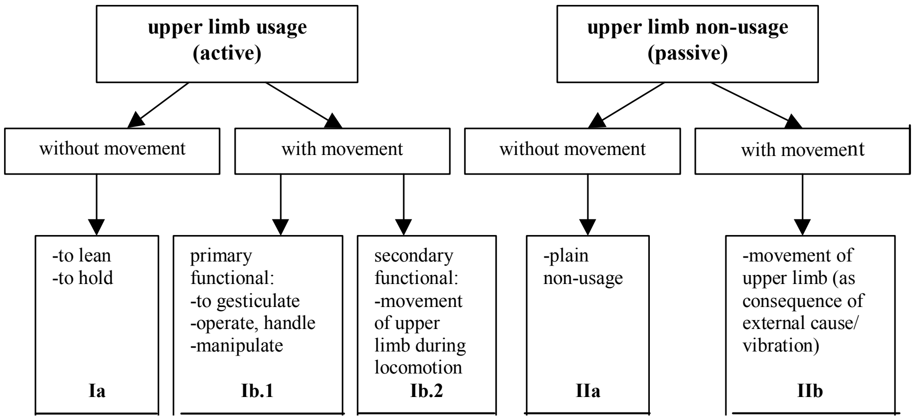
3.3 Method

Three subsequent steps were taken to explore the feasibility: 1) determination of the most appropriate sensor configuration, 2) writing of the 'Upper Limb Usage Analysis Program' consisting of several software algorithms needed for signal processing and analysis, and 3) validating the ULAM and its sensor configuration to discriminate between upper limb usage and non-usage in both healthy subjects and subjects with a disorder involving one upper limb.

Definition and operationalisation of upper limb usage

Upper limb usage can be defined as the movement of parts of the upper limbs. Although upper limb movement is an important aspect of functional upper limb usage, such an approach can lead to validity problems because, in normal daily life, upper limb movements are sometimes non-functional and, *vice versa*, upper limb non-movements are sometimes functional. Therefore, to determine the overall feasibility of the ULAM to measure 24 h real-life upper limb usage, we used the following definition: active movement of (parts of) the upper limb(s) in relation to proximal parts, holding objects and/or leaning. Based on this definition, a framework was compiled to classify upper limb usage and non-usage (figure 3.1).

Figure 3.1: Overview of the different classes of real-life upper limb usage and non-usage based on the following definition of upper limb usage: active movement of (parts of) the upper limb(s) in relation to proximal parts, holding objects and/or leaning.



The key feature of upper limb usage is that it is active ('by the limb itself'). Upper limb usage without movement comprises holding objects and leaning (class Ia). Within the category upper limb usage with movement (Ib) a distinction is made between primary and secondary functional usage. Primary functional upper limb usage (Ib.1) comprises positioning of a limb subsequently to handle (gross movements) or manipulate (fine movements). Class Ib.1 also includes communicative upper limb usage (gesticulation). Secondary functional upper limb usage (Ib.2) comprises movement during locomotion. Secondary functional usage implies that there is no goal of the movements with regard to activities of normal daily living.

The key feature of non-usage is that it is passive. Upper limb non-usage without movement (class IIa) cannot be misunderstood, this is plain non-usage. Upper limb non-usage with movement (IIb), however, requires further explanation. This class was formulated because there are certain activities during which the limb is passively displaced due to body movement (e.g. nervously wiggling, tics, tremors) or external sources (e.g. during riding a car or public transport). Also, in subjects with an upper limb disorder, the involved limb is often passively displaced with the uninvolved limb.

ULAM output categories

We considered the valid detection of primary functional upper limb usage (Ib.1) most important because limitations directly related to upper limb usage are mainly expressed in this form of usage. This choice made discrimination between primary functional usage (Ib.1), secondary functional usage (Ib.2) and plain non-usage (IIa) very relevant. Although we considered upper limb usage without movement (leaning and holding, class Ia) to be of secondary importance, this form was also studied, to determine the overall feasibility of the ULAM. Therefore, upper limb non-usage with movement (IIb) was also taken into account, even though this form was not expected to represent a great part of normal daily life.

We also determined which mobility-related activity was performed each second, because this can improve the detection of upper limb (non-)usage. Combined detection of upper limb (non-)usage and mobility-related activities provides more specific information, because such combinations make up normal daily life. Moreover, activity limitations are, in our opinion, mainly expressed in some specific combinations. These are, for example, primary functional usage during lying, sitting and standing, plain non-usage during sitting and leaning and holding during standing. Hence, for data analysis, three discrete output categories were considered: the five forms of upper limb (non-)usage, the mobility-related activities and, most importantly, certain combinations of forms of upper limb (non-)usage and mobility-related activities.

Subjects

Eight healthy subjects (four male and four female; average age 25.3 (range 21-28) years) volunteered to participate in the first two steps of the study (i.e. to determine sensor configuration and write analysis software). One subject was left handed, seven were right-handed; dominancy was based on writing.

During the third step of the study (validation of the the ULAM), the analysis software was tested on an independent group of eight right-handed subjects (three male and five female): four healthy subjects (average age 24.5, range 21-26 years) and four disabled subjects (average age 44.8, range 26-57 years) with limited upper limb usage due to an upper limb disorder. Three of the latter subjects had limitations at their dominant side and one at the non-dominant side, as a consequence of complex regional pain syndrome type I (n=3) and traumatic injury of the upper limb (n=1). Informed consent was obtained from all subjects.

Activity protocol

To determine the optimum configuration and to write the analysis program (steps 1 and 2), together with an occupational therapist we compiled a list of activities representing the five forms of upper limb usage or non-usage (configuration protocol, table 3.1). The subjects performed these activities in a quasi-natural setting (Occupational Therapy section of the hospital). Subjects were asked to perform activities in their own way and at their own pace. Five subjects performed a short configuration protocol (table 3.1), which represented forms of upper limb non-usage with movement (class IIb, framework) during transportation; these data were used only to determine the most appropriate configuration and not for validation.

After preliminary analysis of the results in this first group of eight healthy subjects, it appeared that upper limb (non-)usage during certain activities (e.g. cleaning the kitchen sink, watching television, washing hands and putting tableware in closet) had agreement percentages of 96-100%. Therefore, to avoid fatiguing the disabled subjects participating in the third study step, we composed a shortened validation protocol with ‘critical’ activities (table 3.1), which had lower agreement percentages in the preliminary analysis. It should be noted that use of such a strict protocol will inevitably have a negative impact on the results.

Apparatus
Uni-axial piezoresistive acceleration sensors (Analog Devices, ADXL201) were used (size 1.0x1.0x0.5 cm). The raw acceleration signals were a combination of two components: the gravitational acceleration and accelerations due to movement and are expressed in g (ms^{-2}) [11, 12]. The magnitude of these components depends on the magnitude and direction of the accelerations with regard to the sensitive direction. Raw acceleration signals were stored digitally on a PCMCIA flash card with a sample frequency of 32 Hz. After measurements, the raw acceleration signals were downloaded onto a PC for analysis. The data recorder is a digital recorder (9.0x15.0x4.5 cm, 700 g) with energy supplied by four penlite batteries.

To detect mobility-related activities, two sensors were placed on the left and right thighs halfway between spina iliaca anterior superior and upper side of the patella (sensitive direction in the sagittal plane) and two sensors on the sternum (sensitive direction in sagittal and longitudinal plane) (figure 3.2). The four remaining sensors were attached on both upper limbs: being in the anatomical position, just proximal from the wrist joint on the forearm, sensitive direction perpendicular to the body segment in the sagittal and transversal directions. The sensors were fixed on Rolian Kushionflex™ or silicone-based stickers (Schwamedico) by double-sided tape; both materials can be fixed directly on the skin.

Figure 3.2: A subject wearing the configuration of the Upper Limb-Activity Monitor with acceleration sensors at the thigh, trunk and forearms.

Table 3.1: Overview of the activity protocols. The configuration protocol was used to determine the sensor configuration and to write analysis software. The validation protocol was used to validate the ULAM.

Activities (indicated per room)	Configuration protocol	Validation protocol
Activities performed in kitchen:		
peel, cut and eat apple	×	×
make fresh orange juice with electric squeezer	×	×
fill water boiler and pour out in bowl	×	×
make instant soup (use scissors), stir and eat it with spoon	×	×
clean kitchen sink and wring out dishcloth	×	
get soap from pump and wash and dry hands	×	
put tableware in closet	×	
Activities performed in living room:		
moving one ('involved') upper limb with other ('healthy')*	×	×
reading newspaper in (easy) chair	×	×
turn pages of book that is lying on table	×	×
watch television while sitting upright	×	
watch television while leaning backwards	×	
act as if being nervous/having tic (moving leg with and without hand on leg)	×	×
make telephone call	×	×
Activities performed in hall and stairwell:		
walk up and down stairs without using banisters	×	×
walk up and down stairs using banisters	×	
place ('involved') limb in protective position near trunk and stand still like this*	×	
walk up and down stairs with limb in protective position*	×	×
walk to and fro in the hall with limb in protective position*	×	
take tray and walk up and down stairs	×	
walk to and fro in hall	×	×
pick up shopping bag and walk to and fro in hall	×	×
pick up and hold umbrella and walk to and fro in hall	×	
Activities performed outside:		
push wheelchair (alternative trolley) on smooth ground	×	
push wheelchair (alternative trolley) on rough ground	×	
ride bicycle on smooth ground	×	×
ride bicycle on rough ground	×	
keep feet still while riding bicycle (alternative moped) on smooth ground	×	×
keep feet still while riding bicycle (alternative moped) on rough ground	×	
Activities performed in hobby room:		
typing on personal computer	×	×
writing on piece of paper with ballpoint	×	×
saw board in two	×	×
vacuum hobby room	×	×
Activities performed in bed and bathroom:		
get undressed and put on nightclothes	×	
brush teeth	×	×
lie in bed on right and left side	×	
read magazine and turn pages in bed while lying on side	×	×
take off nightclothes and get dressed	×	
Activities related to transportation (performed by five subjects):		
sitting in subway	×	
standing in subway	×	
reading book in subway	×	
as passenger in car	×	
driving car	×	

*Indicates patient-specific activities

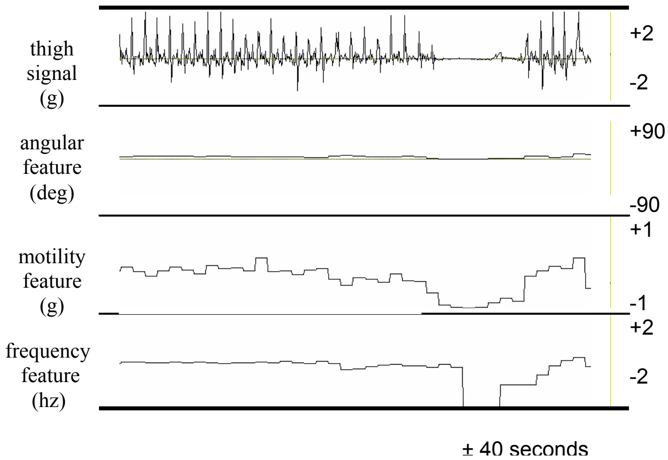
Reference method
Videotape recordings were chosen as the reference method and were recorded together with the acceleration signals. The videotape recordings had a digital time code (resolution of 1 s) that was visible on screen. To allow correct comparison between video data and ULAM data, the timing of the instruments was synchronised: each time a series of activities started and ended, the subjects stood still for 3-5 seconds with both upper limbs flexed 90 degrees at the elbows after which a research assistant tapped one thigh sensor three times (all this was videotaped).

After synchronisation, intervals of various durations (minimum duration > 1 second) were marked on the raw upper limb acceleration signals according to the five forms of upper limb usage and non-usage from the framework. For each subject, for each activity performed, intervals were coded based on the class of usage or non-usage that was displayed on video at that time. Dominant and non-dominant sides were analysed separately, because the form of (non-)usage did not necessarily have to be the same for both upper limbs. The intervals of the eight healthy subjects participating in the first two study steps were used to determine the sensor configuration and to write the analysis program. The intervals of the other eight subjects (four healthy and four disabled) were used to validate the ULAM and to make a statement about feasibility (third step of the study). About 100-120 intervals per subject per side were marked for this latter step.

Detection method: signal processing and analysis
Detection of mobility-related activities was done by standard automatic kinematic analysis using the 'classic activity detection analysis program', which is based on signal processing and inferencing language (SPIL) routines, yielding ´C´-code [13]. For this detection, three feature signals are derived from each raw acceleration signal (sampled at 32 Hz): the angular, frequency and motility feature signals (time resolution 1 s) (figure 3.3).

The angular feature was created after low-pass filtering (finite impulse response, cut-off frequency 0.3 Hz) and subsequent decimation down to 1 Hz and to angles via arcsine transformation (range +90 to –90 degrees). The frequency feature was based upon a band-pass filtered derivative (0.3-2 Hz for the legs; 0.6-4 Hz for the trunk), also using finite impulse response filters. This band-passed signal is the input of the fast time frequency transform (FTFT) procedure [14]. If this signal met the pre-set criteria, a valid frequency was assigned and compressed to 1 Hz. The motility feature was the envelope of AC component above 0.3 Hz and was created after zero-phase finite impulse response high pass filtering (0.3-16 Hz), rectifying and averaging over 1 s. This signal depended on the variability of the raw signal around the mean and was expressed in g (=9.81 ms^{-2}).

Figure 3.3: A raw thigh acceleration signal and its three features (duration approximately 40 seconds).



The subsequent steps for the detection of mobility-related activities were activity detection & post-processing [5-7, 11]. Briefly, for each activity and for each feature signal, minimum and maximum values were pre-set. Each second, the ´distance´ from the actual feature signal value to the pre-set range was calculated. If a feature signal was within this range, this distance was zero, i.e. it did not add to the total distance for that activity. The mobility-related activity with the lowest total distance was detected. There were some (optional) post-processing procedures; activity duration thresholds (using time windows), statistics or reports on duration of activities, or the number of walking periods longer than 10 s. Manual editing was another option during post-processing, which we used (if required) to correct wrongly detected mobility-related activities. This manual editing (with the help of a SPIL routine) was carried out before the upper limb analysis program was applied in the third study step in order to obtain an unobtrusive indication of the feasibility of the ULAM to measure upper limb (non-)usage.

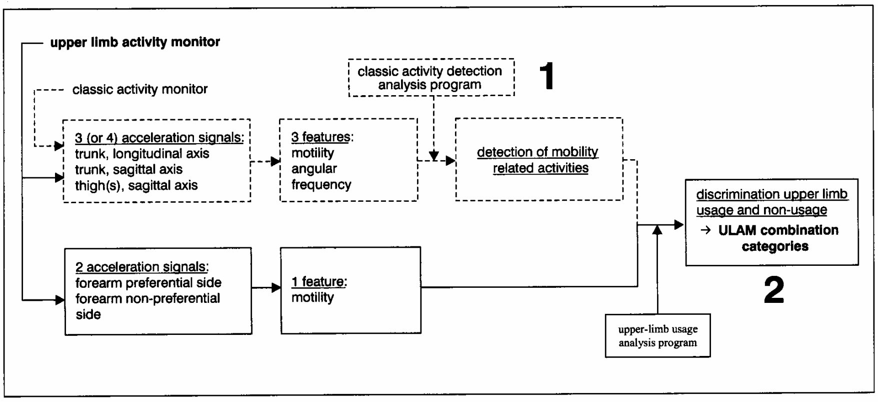
The variability of the raw signal around the mean, as expressed in the motility feature (cutoff frequency 0.3 Hz), can be regarded as a measure of the extent of upper limb movement: the more the limbs are moved, the higher the variability of the raw signal and the higher the motility value. We used the motility feature in all three study steps. To determine the most appropriate sensor position (first step), the average motility values of the marked intervals for the sagittal and transversal upper limb sensors were calculated. The position that yielded the (average) highest motility values for classess of upper limb usage and (average) lowest motility values for classes of upper limb non-usage was considered most appropriate.

To write the software algorithms for the ´upper limb usage analysis program´ (second step) we also used the motility value. Ideally, upper limb usage would result in motility values higher than zero *(mot > 0)* and non-usage would result in motility values of around zero *(mot ≈ 0).* However, we did not expect this ideal situation, because motility values can be similar, for example, during advanced typing and while watching television. Tamura et al. [15] also reported wrist accelerations when a subject was in a sitting position in a chair.

Because mutual exclusiveness between usage and non-usage could not be guaranteed, we set thresholds on the motility values. Motility values exceeding a threshold were regarded as usage and values under a threshold as non-usage. These motility-threshold values could be varied for the different mobility-related activities to compensate for general body movements due to postural sway or head movements. Such general body movements are more prominent during standing than during sitting, and are especially prominent when compared with lying flat. Because of this, upper limb motility during non-usage may have a certain ´basic value´ that is higher during standing than during sitting and/or lying. The motility thresholds providing the least misdetection in the first group of eight subjects were used as algorithms for the ‘upper limb usage analysis program’.

To validate the ULAM and to determine its feasibility (third step), the data from the second group of eight subjects had to be analysed for the three discrete ULAM output categories (see paragraph on ULAM output categories). The ULAM analysis program was based on and included the ‘classic’ activity monitor (figure 3.4). Discrimination between upper limb usage and non-usage was made in two subsequent steps. First, mobility-related activities were detected with the existing classic activity detection analysis program. Subsequently, the upper limb usage analysis program (consisting of SPIL routines, including pre-set motility thresholds) was applied to determine whether or not the upper limbs were used, combining the motility signals from the forearms and the output of the classic activity detection analysis program (i.e. mobility-related activities). The ULAM combination categories were therefore characterised by specific ranges of one or more of the three features derived from the raw acceleration signals.

Figure 3.4: The Upper Limb-Activity Monitor and its analysis program (1+2) in relation to the classic version of the Activity Monitor and its analysis program (1). The 'classic' AM is indicated in patterned grey and black.



To validate the upper limb usage analysis program, we determined the degree to which each videotape category from the framework (representing classes of upper limb usage and non-usage actually performed) was detected correctly by the ULAM. Agreement was calculated according to the equation: agreement for videotape category X = (number of identical samples of videotape recording and ULAM data when videotape category is X / total number of samples for videotape category X) * 100%. Although overall agreement percentages between classic AM output and video recordings for the detection of mobility-related activities have already been described [5-8, 16], we also determined this percentage for the present study.

Statistics

To determine the most appropriate position for the upper limb sensors, average motility values of the sagittal and transversal sensors were compared and analysed using the Wilcoxon matched pairs signed rank sum test. The Wilcoxon matched pairs test was used to determine whether there were unwanted systematic differences in the detection of the five classes of upper limb (non-)usage between the healthy and disabled subjects. For each class of (non)-usage, the Mann-Whitney two samples t-test was used to determine differences in agreement percentages between the healthy and disabled groups. The Mann-Whitney t-test (unequal variances assumed) and the Kruskall-Wallis test were used to determine whether there were any unwanted systematic differences in the discrimination between the dominant, non-dominant, involved and non-involved sides.

3.4 Results

Sensor configuration
For the classes of upper limb usage (Ia, Ib.1 and Ib.2), the sagittal direction resulted in significantly higher motility values than the transversal direction (p=0.001) (table 3.2). There was no significant difference between sagittal and transversal motility values for the forms of upper limb non-usage (IIa and IIb) (p=0.361). The sagittal direction also resulted in higher motility values for upper limb usage and lower values for non-usage for activities related to transportation performed by five subjects (configuration protocol, table 3.1). Therefore, we considered the sagittal sensor most suitable to discriminate between upper limb usage and non-usage: only the sagittal sensor was used during the subsequent study steps.

Upper Limb Usage Analysis Program
Because there was no mutual exclusiveness between usage and non-usage, thresholds for the upper limb usage analysis program were set such that agreement percentages between videotape recordings and ULAM output for the intervals from the first group of subjects were as high as possible for both upper limb usage and upper limb non-usage. In this manner, motility thresholds providing the least misdetection were used as algorithms for the upper limb usage analysis program.

Validating the Upper Limb Usage Analysis Program
For validation, three output categories (mobility-related activities, classes of upper limb (non-) usage and combinations of upper limb (non-)usage and mobility-related activities) were considered separately. The total time analysed was 15 604 samples of 1 s each, which is almost 4.5 hours.

Upper limb (non-)usage
The overall percentage of agreement between videotape recordings and ULAM data for the five classes of upper limb usage and non-usage from the framework was 69.5% (minimum 60.5%, maximum 74.9%, sd 4.8%) (table 3.3). There were no significant differences in agreement percentages between healthy and disabled subjects for these five forms of usage and non-usage (p=0.715).

Table 3.2: Average motility values of sagittal and transversal sensors for the different classes of upper limb usage (Ia, Ib.1 and Ib.2) and non-usage (IIa and IIb). Average motility values were only calculated if a certain form of upper limb usage or non-usage during a certain activity from the Configuration protocol was performed by five or more of the eight subjects participating in the first two steps of the study.

Upper limb usage								Upper limb non-usage			
1a		1b.1		1b.1		1b.2		2a		2b	
sagittal	transversal	sagittal	transversal	sagittal	transversal	sagittal	transversal	sagittal	transversal	sagittal	transversal
0.11	0.14	0.39	0.77	0.13	0.11	0.50	0.35	0.07	0.06	0.52	0.94
0.04	0.02	0.38	0.37	0.49	0.48	0.61	0.52	0.04	0.04	0.41	1.10
0.04	0.04	0.30	0.61	1.24	1.91	0.41	0.36	0.02	0.02	0.58	0.91
0.53	0.50	0.29	0.65	0.62	0.67	0.61	0.51	0.02	0.02	0.10	0.17
0.32	0.35	0.58	0.48	0.74	0.89	0.49	0.37	0.01	0.01	0.11	0.23
0.62	0.48	0.64	0.82	0.34	0.51	0.67	0.46	0.02	0.03	0.25	0.21
0.22	0.17	0.75	0.39	0.40	0.39	0.70	0.56	0.02	0.01		
0.08	0.06	0.44	0.69	0.87	0.69	0.56	0.47	0.12	0.13		
0.15	0.13	0.37	0.21	0.46	0.38	0.61	0.43	0.14	0.13		
0.06	0.03	0.54	0.36	0.37	0.59	0.47	0.37	0.04	0.04		
0.01	0.01	0.39	0.51	0.35	0.72	0.54	0.41	0.08	0.09		
0.07	0.05	1.63	0.67	1.06	0.93	0.57	0.47	0.05	0.02		
0.01	0.01	0.37	0.29	0.65	0.41	0.49	0.44	0.03	0.05		
0.10	0.10	0.30	0.20	0.44	0.20			0.03	0.04		
0.01	0.01	0.11	0.05	0.61	0.29			0.02	0.02		
0.23	0.26	0.40	0.32	0.46	0.29			0.01	0.01		
0.61	0.48	0.14	0.12	0.48	0.37			0.02	0.01		
0.35	0.37	1.14	0.99	0.67	0.65			0.02	0.01		
0.64	0.47	1.35	1.07	1.23	1.06						
0.26	0.21	0.99	0.64	1.75	1.00						
0.21	0.17	1.88	0.98	1.50	0.92						
0.14	0.08	1.72	0.98	0.47	0.60						
0.07	0.11	0.63	0.68	0.36	0.43						
		0.35	0.40	0.87	1.12						
		1.10	1.10	0.08	0.10						
		0.07	0.09	0.53	0.46						
		0.14	0.09	0.80	0.71						
		0.56	0.38	0.52	0.39						
		1.24	1.65	0.11	0.19						
		0.82	0.65	0.45	0.47						
		0.63	0.39	0.61	0.58						
		0.17	0.22	0.88	0.99						
		0.44	0.36	0.39	0.56						
		0.14	0.11	0.97	0.59						
		0.81	0.63	0.28	0.35						

Table 3.3: Overview of total duration (in seconds) and agreement between ULAM output and video recordings (in %) for the five classes of usage described in the framework for the healthy, disabled and total group.

	healthy subjects		disabled subjects		all the subjects	
type of usage	**duration (sec)**	**agreement (%)**	**duration (sec)**	**agreement (%)**	**duration (sec)**	**agreement (%)**
Ia to lean and hold	2706	36.1	1545	38.7	4251	37.0
Ib.1 primary functional usage	4143	81.8	3788	82.6	7931	82.2
Ib.2 secondary functional	513	100.0	459	100.0	972	100.0
IIa plain non-usage	1018	83.7	895	90.1	1913	86.7
IIb involuntary	398	32.3	140	0.0	538	23.9
usage of upper limbs	7362	66.2	5792	72.3	13153	68.9
non-usage of upper limbs	1417	69.2	1034	77.9	2451	72.9
total	8779	66.7	6826	73.1	15604	69.5

The different classes of upper limb usage and non-usage were not equally well detected (table 3.3). Detection of primary functional usage (Ib.1) and plain non-usage without movement (IIa) was good in 82.2% and 86.7%, respectively, of their total duration. Secondary functional usage (Ib.2) was always well detected (100%). Detection of upper limb usage without movement during leaning and holding (Ia) and involuntary/passive non-usage with movement (IIb) was less than optimum, with agreement percentages of 37% and 23.9%, respectively. After separate analysis of the five different classes of usage and non-usage, only the agreement percentages of non-usage with movement (form IIb) showed a significant difference between healthy and disabled subjects (p= 0.004).

Percentage agreement of the ULAM for primary functional usage (Ib.1) (82.2%) was considerably decreased because of wrong detection of operative and/or handling movements of the upper limbs during specific activities (<85%): turning the pages of a book that was lying on a table (52.9%), eating soup or an apple (52.1%), pouring water into bowl (29.2%), moving one ('involved') upper limb with the other ('healthy') limb (55.3%) and reading a magazine in bed and turning the pages (58%). The activities during which manipulative movements of the upper limb were well detected in less than 85% of the time were: writing on a piece of paper (62.6%), stirring soup (53.1%), typing on a PC (77.1%), and pushing buttons to dial a telephone number (77.1%).

There were no systematic differences in the upper limb usage and non-usage agreement percentages between the two groups (p= 0.631). There were also no systematic differences in agreement percentages between the four different sides (p=0.405), between the non-involved and involved sides of the disabled subjects (p= 0.180), between the dominant and non-dominant side of the healthy subjects (p= 0.684), between the non-involved side of the disabled subjects and the dominant side of the healthy subjects (p= 0.191), and between the involved side of disabled subjects and the non-dominant side of healthy subjects (p= 0.704).

Mobility-related activities
Overall agreement between videotape data and ULAM output for mobility-related activities was 94.6%. The 5.4% misdetection was mainly due to general movement, which was detected as cycling. There was no significant difference in agreement percentages between healthy and disabled subjects (p= 0.345) for the various mobility-related activities.

Combination upper limb (non-)usage and mobility-related activities
Agreement percentages for the ULAM combination categories are given in table 3.4. No percentage was calculated for plain non-usage (IIa) during lying down, because there was no activity in the validation protocol that represented this ULAM output category. Holding objects and leaning (Ia) during standing (35.5%) were poorly detected. Some misdetection occurred for primary functional usage (Ib.1), positioning to subsequently handle or manipulate, during lying down (64.3%) and sitting (68.1%) and plain non-usage (IIa) during standing (70.7%). Overall percentage of agreement for the ULAM combination categories was 83.9%.

Table 3.4: Overview of total duration (in seconds) and agreement between ULAM output and video recordings (in %) for several ULAM combination categories.

form of (non)-usage	**mobility-related activity**	**duration (sec)**	**agreement (%)**
primary functional	lying	488	64.3
primary functional	sitting	3558	68.1
primary functional	standing	2639	96.7
primary functional	walking	591	99.8
secondary functional	walking	972	100.0
plain non-usage	lying	(well-detected in configuration protocol)	
plain non-usage	sitting	1293	95.4
plain non-usage	standing	590	70.7

3.5 Discussion and conclusion

General
The aim of this study was to determine the feasibility of an ULAM to discriminate between upper limb usage and non-usage during normal daily life. There were three subsequent steps: 1) determining the most appropriate configuration for the upper limb sensors, 2) writing the upper limb usage analysis program for signal processing and analysis, and 3) validating the ULAM and its sensor configuration to determine the feasibility.

Sensor configuration
With respect to the sensor configuration, using the motility feature, the sagittal direction was the most suitable to discriminate between upper limb usage and non-usage. Because acceleration sensors are not completely waterproof and some subjects cannot bear sensors attached to hand or fingers, two options for forearm attachment we investigated. All subjects considered this to be a convenient solution and all found the ULAM comfortable to wear.

For practical reasons, we did not investigate the possibility of using two- or three-axial sensors. The use of multiple-axial sensors would probably not have influenced our findings because studies using three-axial sensors encountered shortcomings similar to those with the ULAM: i.e. low sensitivity to sedentary activities and inability to register static exercise [17, 18]. In addition, the signals of the two forearm sensors in this study were closely related (correlation of 0.81).

Agreement percentages
Overall agreement between ULAM output and videotape recordings for mobility-related activities (94.6%) was in accordance with earlier studies [5-8, 16]. The overall agreement percentages for (non-)usage during mobility-related activities and the ULAM combination categories were 69.5% and 83.9%, respectively. At first sight these findings may seem somewhat disappointing. However, because the Validation protocol mainly contained the critical activities, this inevitably made the agreement lower. In addition, overall agreement percentages largely depend on the proportion of each category in the protocol used. We considered agreement percentages for each separate form of usage and ULAM output category of greater value than overall percentages, because these proportions are unknown in the real-life situation. These proportions may be totally different from the proportions in the protocol.

ULAM combination categories
As was expected, some of these categories were poorly detected. However, the combinations of upper limb (non-)usage and mobility-related activities that we considered most important were detected satisfactorily. Most of the relatively poor agreement percentages can be explained. Primary functional usage (Ib.1) during lying and sitting had agreement percentages of 64.3% and 68.1%, respectively. Manipulative (fine) movements are practically solely responsible for the low agreement percentages. True non-usage (IIa) (agreement 70.7%) during standing, for example, is poorly detected because, after slight general trunk movements, the upper limbs are also displaced. In view of the technique used, it is logical that holding of objects and leaning (Ia) were most difficult to detect. When holding a cup or reading a book, for example, the upper limbs are displaced as little as possible. The same applies to leaning, which automatically implies absence of movements.

Despite some low agreement percentages, this will not necessarily hamper future usage of the ULAM. In normal upper limb usage leaning and holding, as well as primary functional manipulation, are usually preceded and followed by active upper limb movements to bring the limb in the right position to lean, hold or manipulate. Thus, a well-detectable class of usage in normal daily life situations, usually accompanies poorly detected classes of usage. If a subject has limitations directly related to upper limb usage, then less leaning, holding and manipulating will be performed with the involved side. Most probably, well-detectable movements will also be performed less.

In our opinion, activity limitations in leaning, holding and manipulating will (indirectly) be expressed in the number of upper limb movements. This is in accordance with Taub et al. [19] and Uswatte et al. [20], who also used threshold filters to correct for erratic fluctuations in arm acceleration influencing measurement of the amount of movement. Although, it was not possible to yield a direct measure of the amount of *functional* upper limb *usage*, the amount of upper limb movement was considered a meaningful parameter. It was considered highly likely that an increase in upper limb movement is associated with an increase of usage of that upper limb [20]. With the ULAM it is possible to yield detailed information because mobility-related activities are measured at the same time. Since we used different pre-set motility thresholds for different mobility-related activities to optimise detection, the ULAM combination categories are, in our opinion, even more meaningful parameters.

Possible applications
In this study, the feasibility of the ULAM to measure all forms of upper limb usage and non-usage during normal daily life was investigated. It appeared that the ULAM does not allow valid measurement of every aspect of upper limb usage. However, if outcome measures to determine activity limitations are defined such that upper limb *movement or activity* is measured, we think that future studies will allow to make a statement on the degree of limitations of subjects with an upper limb disorder. Such outcome measures are, for example, the intensity of upper limb activity of the involved side during sitting (expressed in motility values), the absolute extent of upper limb activity of the involved side during standing (expressed at the percentage of the time an upper limb is moved when a subject is standing), or the relative extent of upper limb activity of the involved side relative to the non-involved side during lying. Such outcome measures can be used to determine activity limitations of subjects with neurological disorders, musculoskeletal disorders or chronic (benign) pain, to monitor natural recovery, to determine treatment effects or to describe the relationship between impairments and activity limitations, provided that it is emphasized exactly how activity limitations are defined.

Current developments
The development of an instrument such as the ULAM is an ongoing process of extending possibilities and optimising properties. We are currently working on the automatic detection of activities related to transportation and wheelchair driving that, until now, could only be determined by visual inspection. In addition, dimensions,

weight and impermeability to water of the data recorder can also be improved. In the current version of the classic activity detection analysis program, the pre-set feature ranges for cycling have been redefined and a time window has been included for cycling, which rejects a period of cycling of less than 10 seconds duration, hereby improving misdetection of mobility-related activities.

It is not yet possible to automatically discriminate between primary and secondary functional usage during walking, i.e. to determine whether a subject is performing ordinary walking or carrying a bag while walking. Currently, this can only be done by visual inspection. Since the acceleration signals and its derived features certainly differ between these types of upper limb usage, calibrating the ordinary walking of a subject at the beginning of a measurement period may be a solution.

Other techniques
Upper limb movements have a non-cyclic character and many degrees of freedom. Therefore, use of the motility feature alone is not sufficient to discriminate between functional upper limb usage and non-usage. The motility feature is a technique comparable to the more often used Wrist Activity Monitor/Actometer/Actigraph [21-25]. The additional value of the ULAM, however, is the combination of both mobility-related activities and upper limb motility scores, plus the fact that both upper limbs are measured. Improved detection of upper limb usage and non-usage may be achieved with electromyogram (EMG) recordings in addition to accelerometers. Keil and colleagues [26] considered the two techniques complimentary and suggested to use them simultaneously. However, this may not be desirable, because ambulatory EMG measurement during a 24-hour period is not yet feasible or convenient for the subjects.

Systematic differences
No differences in agreement percentages were found, except for a significant difference between healthy and disabled subjects for upper limb non-usage class IIb. However, this latter form of usage represents a very small proportion of the total time analysed and it is questionable what part of 24-hour real life it will represent. We focused on systematic differences, because the absence of such differences allows comparison between disabled and healthy subjects. The presence of systematic differences would hamper use of the ULAM in future patient studies.

3.6 Conclusion

Although, the ULAM, with its two additional sensors on the forearms, does not yet allow valid measurement of *every* aspect of upper limb (non-)usage, its use is considered feasible in future studies in subjects with upper limb disorders to discriminate between upper limb usage and non-usage during performance of mobility-related activities to determine activity limitations.

3.7 References

1. Richards JM, Jr., Hemstreet MP. Measures of life quality, role performance, and functional status in asthma research. Am J Respir Crit Care Med 1994; 149:S31-9; discussion S40-3.
2. Duckworth D. Measuring disability: the role of the ICIDH. Disabil Rehabil 1995; 17:338-43.
3. Geurts ACH, Mulder T, R.A.J. R, Nienhuis B. From the analysis of movement to the analysis of skills: bridging the gap between laboratory and clinic. J. Rehabil. Sciences 1991:9-12.
4. Keith RA. Functional status and health status. Arch Phys Med Rehabil 1994; 75:478-83.
5. Bussmann JBJ, Reuvekamp PJ, Veltink PH, Martens WL, Stam HJ. Validity and reliability of measurements obtained with an "activity monitor" in people with and without a transtibial amputation. Phys Ther 1998; 78:989-98.
6. Bussmann JBJ, Tulen JH, van Herel EC, Stam HJ. Quantification of physical activities by means of ambulatory accelerometry: a validation study. Psychophysiology 1998; 35:488-96.
7. Bussmann JBJ, van de Laar YM, Neeleman MP, Stam HJ. Ambulatory accelerometry to quantify motor behaviour in patients after failed back surgery: a validation study. Pain 1998; 74:153-61.
8. Tulen JH, Bussmann HB, van Steenis HG, Pepplinkhuizen L, Man in 't Veld AJ. A novel tool to quantify physical activities: ambulatory accelerometry in psychopharmacology. J Clin Psychopharmacol 1997; 17:202-7.
9. Tulen JH, Stronks DL, Bussmann JB, Pepplinkhuizen L, Passchier J. Towards an objective quantitative assessment of daily functioning in migraine: a feasibility study [In Process Citation]. Pain 2000; 86:139-49.
10. Bussmann JBJ, Veltink PH, Koelma F, Lummel RCv, Stam HJ. Ambulatory monitoring of mobility-related activities; the initial phase of the development of an Activity Monitor. Eur J Phys Med Rehabil 1995:2-7.
11. Bussmann JBJ, Martens WLJ, Tulen JHM, Schasfoort FC, Berg-Emons HJGvd, Stam HJ. Measuring daily behaviour using ambulatory accelerometry: the Activity Monitor. Behavior Research Methods, Instruments & Computers 2001; 33:349-56.
12. Veltink PH, Bussmann HB, de Vries W, Martens WL, Van Lummel RC. Detection of static and dynamic activities using uniaxial accelerometers. IEEE Trans Rehabil Eng 1996; 4:375-85.
13. Jain A, Martens WLJ, Mutz G, Weiss RK, Stephan E. Towards a comprehensive technology for recording and analysis of multiple physiological parameters within their behavioral and environmental context. In: Fahrenberg J, Myrtek M, eds. Ambulatory assessment; computer-assisted psychological and psychophysiological methods in monitoring and field studies. Seatle: Hogrefe&Huber Publishers, 1996:215-236.
14. Martens WLJ. The Fast Time Frequency Transform (F.T.F.T.): a novel approach to the Instantaneous Spectrum. Proceedings IEEE Engineering in Medicine & Biology Society 1992.
15. Tamura T, Fujimoto T, Sakaki H, Higashi Y, Yoshida T, Togawa T. A solid-state ambulatory physical activity monitor and its application to measuring daily activity of the elderly. J Med Eng Technol 1997; 21:96-105.
16. Berg-Emons HJGvd, Bussmann JBJ, Balk AHMM, Stam HJ. Validity of ambulatory accelerometry to quantify physical activity in heart failure. Scand. J. Rehab. Med. 2000; 32:187-192.
17. Bouten CV, Koekkoek KT, Verduin M, Kodde R, Janssen JD. A triaxial accelerometer and portable data processing unit for the assessment of daily physical activity. IEEE Trans Biomed Eng 1997; 44:136-47.
18. Matthews CE, Freedson PS. Field trial of a three-dimensional activity monitor: comparison with self report. Med Sci Sports Exerc 1995; 27:1071-8.
19. Taub E, Uswatte G, Pidikiti R. Constraint-Induced Movement Therapy: a new family of techniques with broad application to physical rehabilitation--a clinical review. J Rehabil Res Dev 1999; 36:237-51.
20. Uswatte G, Miltner WH, Foo B, Varma M, Moran S, Taub E. Objective measurement of functional upper-extremity movement using accelerometer recordings transformed with a threshold filter. Stroke 2000; 31:662-7.
21. Patterson SM, Krantz DS, Montgomery LC, Deuster PA, Hedges SM, Nebel LE. Automated physical activity monitoring: validation and comparison with physiological and self-report measures. Psychophysiology 1993; 30:296-305.
22. Renfrew JW, Moore AM, Grady C, et al. A method for measuring arm movements in man under ambulatory conditions. Ergonomics 1984; 27:651-61.
23. Renfrew JW, Pettigrew KD, Rapoport SI. Motor activity and sleep duration as a function of age in healthy men. Physiol Behav 1987; 41:627-34.
24. van Hilten B, Hoff JI, Middelkoop HA, et al. Sleep disruption in Parkinson's disease. Assessment by continuous activity monitoring. Arch Neurol 1994; 51:922-8.
25. van Vugt JP, van Hilten BJ, Roos RA. Hypokinesia in Huntington's disease. Mov Disord 1996; 11:384-8.
26. Keil A, Elbert T, Taub E. Relation of accelerometer and EMG recordings for the measurement of upper extremity movement. Journal of Psychophysiology 1999; 13:77-82.