MEASURING PHYSICAL BEHAVIOR AFTER STROKE

Sedentary behavior, body postures & movements, and arm use

Malou H. J. Fanchamps

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Measuring Physical Behavior after Stroke

Sedentary behavior, body postures & movements, and arm use

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Sedentair gedrag, houdingen & bewegingen en arm gebruik

Proefschrift

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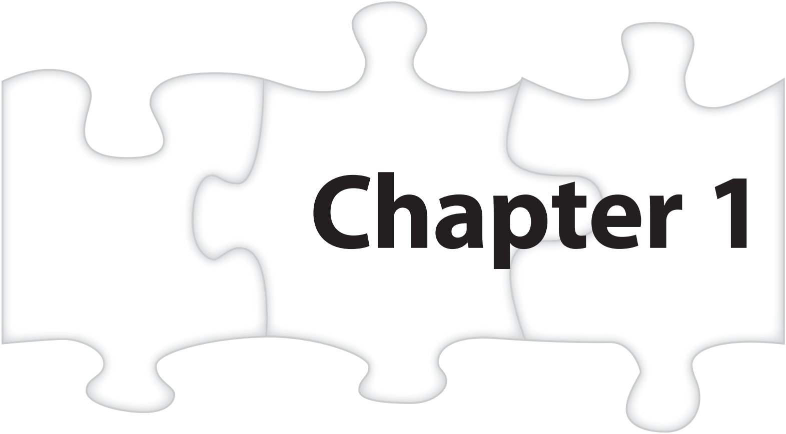

Chapter 1

General introduction

The title of this thesis contains the three key elements: **measuring**, **physical behavior**, and **stroke**. This chapter introduces these elements in the reversed order, leading to the aims and the outline of this thesis.

STROKE

Neurological dysfunction caused by an infarction or a bleeding of the brain circulation is called a stroke. In the Netherlands, about 39,000 people suffer from a stroke each year and about 9,200 people die each year as the result of a stroke [1]. After surviving the acute phase of a stroke, more than half of these people are more or less dependent on others for daily-life functioning [2, 3], making stroke the leading cause of adult disability [4]. From the perspective of the International Classification of Functioning, Disability and Health (ICF) (Figure 1.1) [5], a stroke can disturb several *Body Functions and Structures* such as psychological, emotional, social, sensor, and motor. Disturbed motor body functions can range from minor coordination deficits to complete paralysis. These disturbed motor functions lead to constraints in the *Activities* domain, which is divided into *Capacity* and *Performance,* and can, for example, be defined as the use of an assistive device, the ability to self-care, or a person's physical behavior. In turn, disorders in the *Activities* domain might affect the *Body Functions and Structures* domain, and have an effect on the *Participation* domain. Since, until now, there is no cure for a stroke, stroke rehabilitation aims to improve the domains *Body Functions and Structures*, *Activities*, and *Participation* while coping with the remaining disabilities [6].

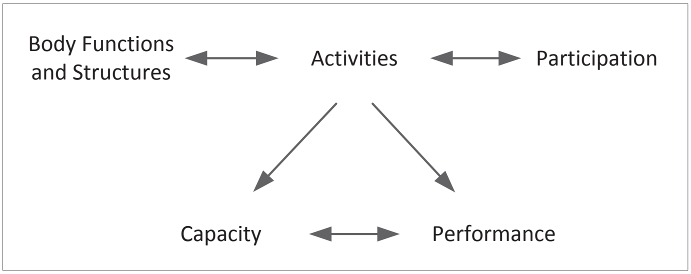

Figure 1.1 Three domains and two qualifiers of the ICF model.

PHYSICAL BEHAVIOR

In this thesis, the *Performance* qualifier of the *Activities* domain is defined as a person's physical behavior. This is what a person actually performs, not his/her capacity to do this. Physical behavior is an umbrella term for all behaviors of a person related to body postures, movements, and physical activities in daily life [7]. Components of physical behavior include, for example, physical activity, body postures & movements, transitions between body postures & movements, quality of movements, sedentary behavior, and arm use. In this thesis, three components of physical behavior are studied: i) sedentary behavior, ii) body postures & movements, and iii) arm use.

Sedentary behavior

Sedentary behavior is defined as *'any waking behavior characterized by an energy expenditure ≤1.5 metabolic equivalents (METs) while in a sitting, reclining, or lying posture'* [8] and is negatively related to morbidity and mortality, irrespective of physical activity [9, 10]. Both sedentary behavior and moderate-vigorous physical activity can be accumulated in large amounts in the course of one day. Thus, besides being sufficiently physically active, reducing sedentary behavior should be a goal to attain a healthy lifestyle. In both preventing and recovering from a stroke, sedentary behavior plays an important role. First, sedentary behavior is a risk factor for the occurrence and recurrence of a stroke [11]. Second, sedentary behavior has a deconditioning effect on the locomotion system and hinders motor function recovery [12]. Therefore, after a stroke, it is even more important for people to reduce sedentary behavior than for the general population.

Body postures & movements

Body postures & movements are literally the postures and movements a person performs, like sitting, standing, walking, etc. After surviving a stroke, it can be a considerable challenge to perform more active body postures & movements (such as standing and walking) due to disturbed motor functions [13]. From the perspective of motor recovery, it is important to study body postures & movements, rather than the levels of physical activity. This is because, from the perspective of energy expenditure, sitting and standing are almost similar [14-16], whereas they are not similar from the perspective of motor recovery [12]. Therefore, it is more relevant to avoid too much time lying or sitting and promote upright activities (e.g. standing, walking) to stimulate motor recovery, than to reach a certain level of energy expenditure. Thus, body postures & movements are an important aspect of stroke rehabilitation. Moreover, information on body postures & movements is needed to measure sedentary behavior according to its two-component definition. The information on body postures & movements is also useful when measuring arm use, to distinguish arm movements during walking from those during sitting or standing.

Arm use

The arms are important in the performance of many daily-life activities. However, after a stroke, these activities can be difficult to perform due to a paretic arm. About 75% of stroke survivors initially have problems using their paretic arm in daily life and about 65% of them still have this problem after six months [17, 18]. Limited arm function may cause problems in using the arm to perform daily-life activities and, as a consequence, in participating in social activities and at work; therefore, it is also associated with a poorer quality of life [19]. A limited arm function is not the only cause of these problems. A discrepancy between capacity and performance, *what a person can do (arm function)* versus *what he/she actually does (arm use),* can play a role as well. This discrepancy (also known as 'non-use') is a major issue after a stroke [20]. Therefore, it is important to integrate both *arm function* and *arm use* as outcome measures in stroke rehabilitation.

MEASURING PHYSICAL BEHAVIOR

Physical behavior can be measured using several methods. Simple, inexpensive and widely applicable methods include self-reports, proxy-reports, and questionnaires. However, important disadvantages of these methods are recall bias, social desirability, and subjectivity [21, 22]. Especially for people after stroke, using reports and questionnaires can be difficult due to cognitive and/or communicative impairments. In order to gain valid data on the physical behavior of people after stroke, ambulatory measurements are needed. This means continuously measuring a free moving person in his/her own environment in everyday life, i.e. ambulatory monitoring [23]. A preferred technique for this is accelerometry because it is relatively inexpensive, easy-to-use, and widely applicable. Accelerometry measures accelerations, which are the result of gravity and movements of the human body. Data on these accelerations can provide detailed information about different components of physical behavior [24]. Based on accelerations, movement counts can be calculated to determine a person's energy expenditure and arm movement intensity, which can be translated into arm use. In addition, accelerations can be used to determine the performed body postures & movements by determining the orientation of the sensor relative to gravity.

Until recently, accelerometer-based activity monitors were often multi-sensor systems which involved low levels of wearing comfort and required complex data processing software. Due to various technological developments, nowadays, the devices are smaller, wireless and generally one-sensor systems, with user-friendly software. Despite the enormous supply of new devices, not all of them are clinically applicable, mainly due to the lack of validation. Worldwide, people after stroke represent a large group with a high economic burden; therefore, it is important to be able to measure their physical behavior in a valid way. A population-specific validation study is needed, because movement patterns can change after a stroke [25]. Although the Activ8 Physical Activity Monitor (the Activ8) [26] is a promising device to measure body postures & movements and their intensities in stroke rehabilitation, it has not yet been validated for use in people after stroke. This activity monitor can also be the basis of an arm use monitor. However, before this arm use monitor can be used in stroke rehabilitation, it needs to be further developed and validated.

To measure physical behavior, the component of interest has to be translated into a measurable variable, this is called 'operationalization'. Even when the outcome measure has been operationalized, different ways of calculating the measure might still exist. In literature, many different types of operationalization and ways of calculation have been used for the components of physical behavior. This makes it difficult to compare studies and hinders progress in developing knowledge on physical behavior and health. For example, sedentary behavior is often operationalized as 'the amount of time someone sits' [27, 28], or 'the amount of time with low energy expenditure' [29, 30]. Although both are operationalizations of sedentary behavior, two different things are measured. The effect of those different operationalizations of sedentary behavior on the outcomes describing sedentary behavior has not yet been examined.

In the end, the aim is to measure physical behavior in stroke rehabilitation. Measuring energy expenditure and body postures & movements can provide information about a person's sedentary behavior and motor recovery during stroke rehabilitation. Moreover, measuring arm use together with the arm function can provide important information about non-use. Nevertheless, since it remains unclear how arm use recovers and how it is related to arm function, measuring these two aspects can contribute to knowledge elucidating the issue of non-use. Also, the information on other components of physical behavior can expand our knowledge on recovery after a stroke. All that information can also be used in clinical practice to personalize stroke rehabilitation, e.g. to provide a person with feedback about his/her arm use and to stimulate him/her to increase this arm use by using his/her arm capacity to its full ability.

OBJECTIVES AND OUTLINE OF THIS THESIS

As described above, measuring physical behavior involves important methodological aspects to be considered before using ambulatory monitoring to measure physical behavior in daily life. The primary aim of this thesis was to investigate two methodological aspects from the perspective of stroke rehabilitation. Another aim was to describe daily-life arm use in people in the subacute phase after a stroke. Figure 1.2 presents an outline of the chapters of this thesis and their relation with the methodological aspects and the components of physical behavior.

First, the effect of different operationalizations is studied in the component 'sedentary behavior'. In ***Chapter 2***, this effect is assessed in healthy people. ***Chapter 3*** describes data of people after stroke, because different movement patterns could influence the effect studied. Second, the validity of two specific devices is assessed. In ***Chapter 4***, the validity of the Activ8 is evaluated to measure body postures & movements in people after stroke, and ***Chapter 5*** describes the development and validation of the Activ8 arm use monitor (the Activ8-AUM) in this population. In addition to the chapters addressing the methodological aspects of measuring physical behavior, in ***Chapter 6*** the validated Activ8-AUM is used to measure arm use during stroke rehabilitation. The recovery of arm use is described in a longitudinal study during the first six months after a stroke, and it is related to the recovery of arm function during the same period.

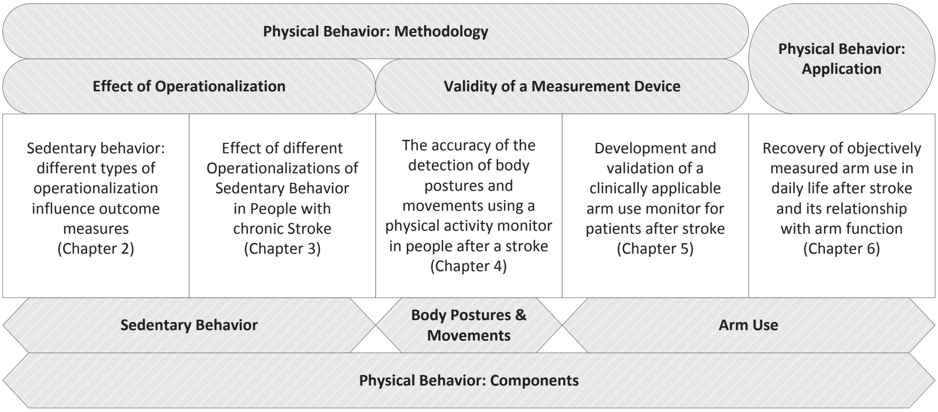

Figure 1.2 Overview of the content of this thesis.

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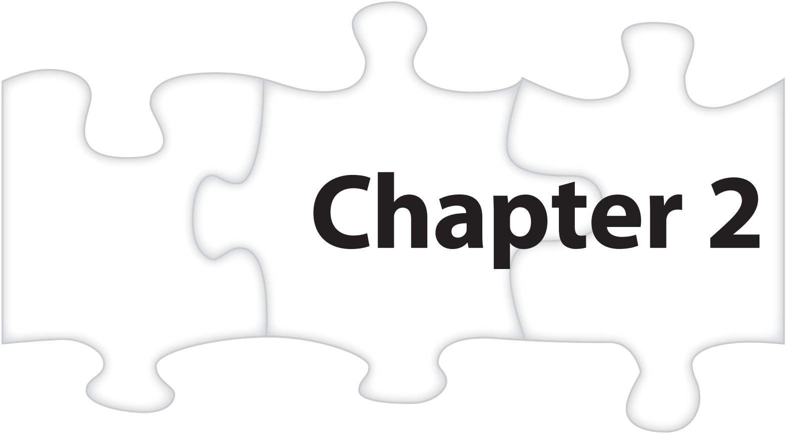

Chapter 2

Sedentary behavior: Different types of operationalization influence outcome measures

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ABSTRACT

Introduction: Sedentary behavior (SB) influences health status independently of physical activity. The formal definition of SB is: "any waking behavior characterized by an energy expenditure ≤1.5 METs while in a sitting or reclining posture". However, measuring SB mostly does not include both the intensity and postural component. The aim of this study was to quantify the effect of type of operationalization of SB on total sedentary time and the pattern of SB.

Methods: 53 healthy subjects were measured 24h with a multi-sensor activity monitor that provides a valid one-second detection of body postures and movements and a calculated intensity measure. The SB outcome measures were: total sedentary time; number of sedentary bouts; mean bout length; fragmentation; and W-index. All outcomes were calculated for three types of operationalization of SB: 1) waking time in lying and sitting posture and below the sedentary intensity threshold (<0.016g comparable with Actigraph <150 counts, COMBI); 2) waking time in lying and sitting posture (POST); 3) waking time below the sedentary intensity threshold (<0.016g, INT). Outcome measures based on these three operationalizations were compared with repeated measures ANOVA.

Results: Total sedentary time was significantly different (p<.001) between all three conditions: 505.8 (113.85) min (COMBI), 593.2 (112.09) min (POST), and 565.5 (108.54) min (INT). Significant differences were also found for other outcome measures.

Conclusion: Our study shows that type of operationalization significantly affects SB outcome measures. Therefore, if SB is defined according to the formal definition, measurements must include both the intensity and postural component.

INTRODUCTION

In the initial stages of promoting an active and healthy lifestyle, research and guidelines mainly focused on total amount of physical activity (PA)[1], such as total number of steps and amount of time of moderate-to-vigorous PA. However, over the last-decade research has shown that sedentary behavior (SB) is also a determinant of health independent of the amount of PA[2,3]. As a result, lifestyle interventions should not only aim at optimizing PA, but also at reducing SB.

For clarity, a consistent definition of SB is proposed: any waking behavior characterized by an energy expenditure ≤1.5 metabolic equivalents (METs) and a sitting or reclining posture[4]. This definition indicates that two behavioral components are crucial: an intensity/energy expenditure component and a postural component. However, in SB research typically only one of these components is assessed. For example, in many studies total sedentary time and sedentary bouts are calculated from objectively measured epochs characterized by movement counts below a specified threshold, where that threshold is generally assumed to represent 1.5 METs[5,6]. This intensity approach has its origin in a huge amount of available devices that measures acceleration and convert this into counts as their output, representing the intensity of the movement. On the other hand, some studies mainly focus on the postural component of the SB definition, e.g., by assessing the amount of sitting/reclining[7,8]. Thus, so far SB has rarely been measured objectively according to its formal two-component definition.

SB research is thus characterized by a variety in operationalization of SB, and in methods how SB is measured. This variety hinders progress, because results of studies may depend on the way SB is operationalized[7,9]. Consequently, results cannot be compared between studies, and the process of obtaining insight in the working mechanisms of SB is hindered. In addition, SB outcome measures should not only include the total amount of SB, but also data on bouts of SB, as there is some evidence that not only is the amount of SB important, but also the pattern by which sedentary time is accumulated[5,10]. So far, the effect of different types of operationalization of SB on SB outcome measures has not been quantified. A currently available data set containing objectively measured data of both the intensity and postural component, allows quantification of this effect. The aim of this study was therefore to quantify the effect of the type of operationalization of SB on SB outcome measures. SB was studied using only the intensity data, only the postural data, and data of both components.

METHODS

Study sample

Data was used from previous studies in which healthy people were control subjects for patients with chronic conditions[11-14]. Besides matching for age and gender there were no specific inclusion or exclusion criteria for these healthy control subjects. We used no other selection criteria for using the existing data, except that raw data had to be available. For this explorative study, no sample size calculation was performed, all available data was used. We included data from 53 healthy subjects, 19 male and 32 female; information of gender was missing for 2 subjects. The subjects had a mean (SD) age of 48.4 (14.6) years. All subjects gave their informed consent and all studies were approved by the medical ethical committee of the Erasmus MC.

Measurements

SB was objectively measured with the Vitaport activity monitor (TEMEC, Kerkrade, The Netherlands) which is based on long-term measuring of signals from body-fixed accelerometers. The device is valid to quantify a set of body posture and movements (P&M, e.g., sitting, standing, and walking)[15-17], provides information on the duration of these activities, and is applied in various descriptive, evaluative, and comparative studies[18]. Besides the duration of P&M, information which is related to the intensity of the P&M can be obtained, and was shown to correlate well with oxygen uptake and heart rate[19]. The device consists of three body-fixed accelerometers, one attached to each thigh (uni-axial) and one to the trunk (sternum position, bi-axial). The accelerometers sampled with 128 Hz, and were connected to the data recording unit worn around the waist, which stored the data with 32 Hz. Subjects were instructed to continue their ordinary daily life and to wear the device continuously; however, bathing, showering, and swimming was not possible during the measurement period. The principles of the activity monitor were only explained after study completion to avoid measurement bias. The measurements had a minimum duration of one full-day (24h), and were conducted during consecutive weekdays.

Data processing

If Vitaport measurements consisted of several days, the first full-day was used for analysis. According to the definition of SB only data from waking hours was used. We determined the start and end of these waking hours by inspection of the raw signals and used the diaries filled out by the subjects during the measurement. In case of uncertainty, agreement with a second researcher was obtained.

The subsequent steps of the Vitaport for the activity detection and its post processing were described previously[20]. Briefly, the Vitaport automatically detects each second a P&M (lying, sitting, standing, walking, cycling, and general noncyclic movements). This detection is based on feature signals (the angular, motility, and frequency feature; all 1Hz) derived from each raw acceleration signal, activity-specific settings, and a minimal distance-based detection method. We used this standard output signal as postural component. For the intensity component we used the body motility output which is the average of the motility feature signal of each sensor. This motility depends on the variability around the mean of the raw acceleration signal, and is created by high pass filtering (0.3Hz), rectifying and averaging over 1 s, and is expressed in g (9.81m/s2). The body motility output is comparable with the output of devices which provide a movement intensity measure (counts); however, there is no threshold for SB for this body motility output known yet. Therefore, we performed some extra measurements in which we simultaneously used the Vitaport and Actigraph (GT3X, Actigraph, Pensacola, Florida, USA). This is a well-known tri-axis accelerometer with movement counts as output, and frequently used to measure SB. During those measurements 8 healthy subjects (2 men; mean age 31 years), performed various activities (sitting, standing and, walking) with different intensities. After these measurements, we related the Actigraph movement counts with the synchronous Vitaport body motility output. As expected, these were strongly related ($R=0.9$, $p<0.001$), and from that relationship we could determine a threshold for SB for the Vitaport body motility output. A threshold of 150 Actigraph movement counts[21] corresponded with a Vitaport body motility value of 0.016g. The body motility output was converted into a binary time series (0/1) with "1" expressing seconds that were below the threshold of 0.016g and thus classified as sedentary. Thereafter a duration threshold of 5 s was applied, to perform comparable post processing of the body motility than of the P&M detection incorporated in the analysis of Vitaport itself[20].

Outcome measures

SB outcome measures were calculated for the three types of operationalization of SB:

- Combined operationalization: waking time in lying and sitting posture with a low intensity (<0.016g, comparable with Actigraph <150 counts).
- Posture operationalization: waking time in lying and sitting posture.
- Intensity operationalization: waking time with a low intensity (<0.016g, comparable with Actigraph <150 counts).

For each operationalization we quantified SB by calculating several outcome measures using a custom-made Matlab program. In this program, new binary (0/1) time series were created for each operationalization of SB, with "1" expressing seconds that satisfied that operationalization. In this way SB bouts (periods of uninterrupted samples of SB) were created. Due to the "5 seconds rule" applied to the posture/movement detection by Vitaport and to the METs time series in our analysis, bouts and periods between bouts last at least 5 seconds.

Subsequently, for each of three binary SB time series the following SB outcome measures were calculated:

1. Total sedentary time (minutes): absolute total time of SB.
2. Number of sedentary bouts: number of uninterrupted periods of SB.
3. Mean bout length (seconds): since the length of the bouts was log normally distributed, the mean of the natural log of the data was calculated and back transformed into the original scale.
4. Fragmentation: number of bouts divided by total sedentary time[22]. A higher fragmentation indicates a more fragmented time spent sedentary. This means there are less prolonged uninterrupted bouts.
5. W-index: the fraction of the total time accumulated in bouts longer than the median bout length[23].

Statistical analysis

Statistical analysis was performed with SPSS software version 21. Repeated measures ANOVA with the different types of operationalization of SB as within subject variable were performed to assess the effect of operationalization on each of the SB outcome measures separately. Maulchy's test was used to test sphericity, and in cases of sphericity violations, Greenhouse-Geisser estimates were used for correcting the degrees of freedom of the F-tests. Significance levels were set at p <.05 and Bonferroni corrections were used to correct for multiple pairwise comparisons. Besides calculating results, they were also visualized in scatterplot.

RESULTS

Overall and in the post-hoc analysis a significant difference between the types of operationalization of SB for all outcome measures was found (Table 2.1 and 2.2). It can be seen that the amount of SB was lower when measured with the intensity operationalization (mean 565.5, SD 108.54 min) than with the posture operationalization (mean 593.2, SD 112.09 min). There was even less sedentary time when measured with the combined operationalization. This is also seen in the scatterplot were most values of posture vs intensity were below the line x=y and above that line in the other two comparisons (Figure 2.1). The results of the number of sedentary bouts and the fragmentation were similar: in both outcome measures the intensity operationalization was highest (number of bouts: mean 336.6, SD 110.75; fragmentation: mean 0.628, SD 0.2712) and the posture operationalization lowest (mean number of bouts 86.2, SD 31.72; mean fragmentation 0.152, SD 0.0727). The values in the scatterplots for these outcome measures containing the intensity operationalization were above the line x=y. The results of the mean bout length had a reversed pattern compared to the result of the number of sedentary bouts

Table 2.1 Results of the repeated measures ANOVA, focusing on the effect type of operationalization of SB on SB outcomes.

Outcome measure	**Sphericity** χ^2 **, df=2 *(p-value)***	**Correction df with Greenhouse-Geisser**	***F*-test, *(p-value)***
Total sedentary time (min)	31.86 *(0.000)*	ε=0.68	*F*(1.37, 71.01) = 78.3, *(0.000)*
Number of sedentary bouts	9.36 *(0.009)*	ε=0.86	*F*(1.71, 89.07) = 256.8, *(0.000)*
Mean bout length (sec)	37.99 *(0.000)*	ε=0.66	*F*(1.31, 68.19) = 125.4, *(0.000)*
Fragmentation	33.18 *(0.000)*	ε=0.68	*F*(1.35, 70.36) = 169.1, *(0.000)*
W-index	17.85 *(0.000)*	ε=0.77	*F*(1.54, 80.29) = 23.9, *(0.000)*

Table 2.2 Mean values (SD) of all outcome measures of the three operationalization of the chosen threshold.

Outcome measure	**Threshold 0.016g**	**P value**	**%**
Total sedentary time (min)		> 0.01	
Combined	505.8 (113.85)		100
Posture	593.2 (112.09)		117
Intensity	565.5 (108.54)		112
Number of bouts		> 0.001	
Combined	204.8 (99.84)		100
Posture	86.2 (31.72)		42
Intensity	336.6 (110.75)		164
Mean bout length (sec)		> 0.001	
Combined	72.2 (31.68)		100
Posture	148.6 (66.73)		206
Intensity	38.9 (10.37)		54
Fragmentation		> 0.001	
Combined	0.428 (0.2434)		100
Posture	0.152 (0.0727)		36
Intensity	0.628 (0.2712)		147
W-index		> 0.01	
Combined	0.912 (0.0268)		100
Posture	0.937 (0.0229)		103
Intensity	0.925 (0.0267)		101

P value is the largest p values of all three post-hoc combinations (combined vs posture; combined vs intensity; posture vs intensity). Total sedentary time: combined vs posture p> 0.001; combined vs intensity p> 0.001; posture vs intensity p> 0.01. W-index: combined vs posture p> 0.001; combined vs intensity p> 0.001; posture vs intensity p> 0.05.

and the fragmentation. The W-index results were similar to the result of total sedentary time, however in the scatterplots can be seen that there is more spread around the line x=y. In addition, not all scatterplots follow the line x=y: the scatterplots of the number

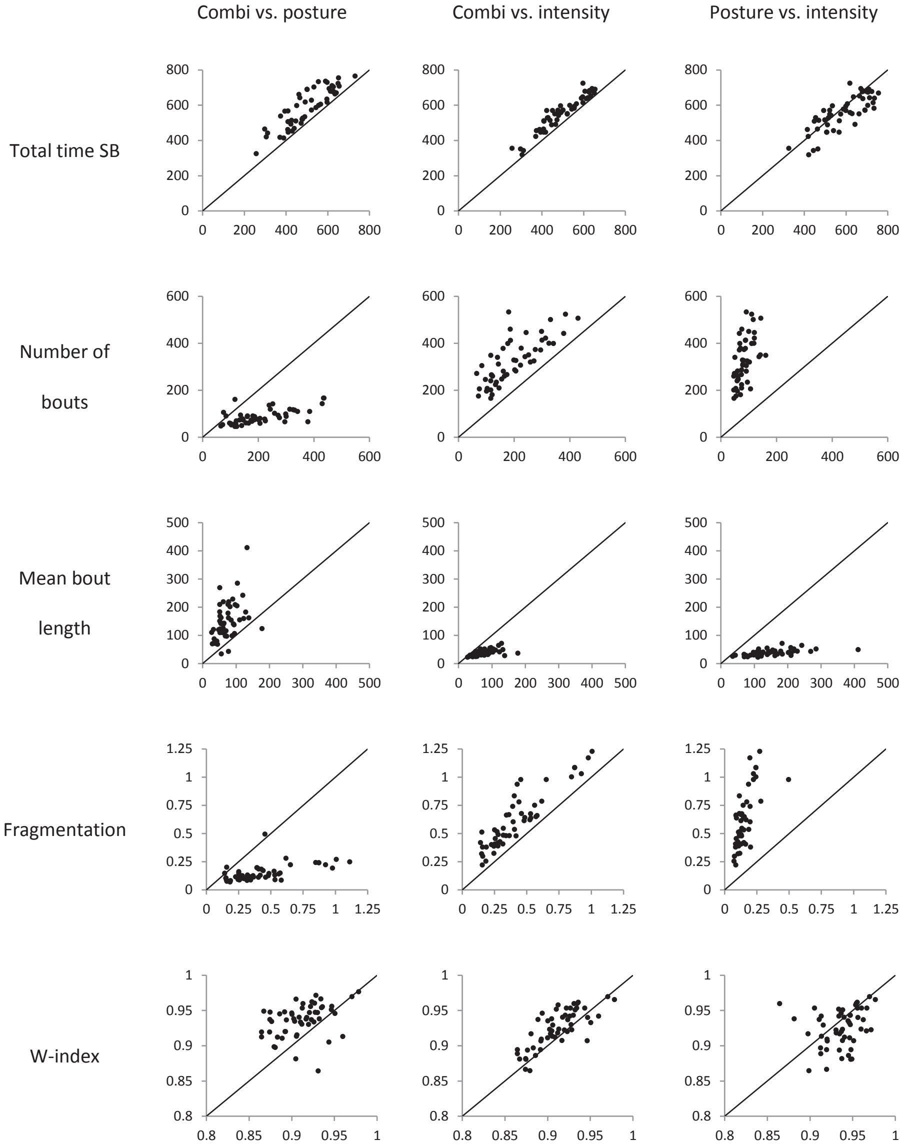

Figure 2.1 Scatterplots of all outcomes in which three operationalizations are visualized. First mentioned operationalization is on the x axes, second one on the y axes.

of bouts and fragmentation of 'posture vs intensity' is very steep, while the mean bout length and the W-index of 'combi vs posture' is more round.

DISCUSSION

The aim of this study was to quantify the effect of the type of operationalization of SB on SB outcome measures. We showed that the type of operationalization significantly affects the total sedentary time and the pattern how this time is accumulated. The results were not only statistically significant, but can also be considered relevant. For example, when considering the combined operationalization as 100% – which includes both the posture and intensity component in line with the definition – the total time of the postural operationalization is about 117% and that of the intensity operationalization 112%. However, in the distribution of this time, even much larger differences were found. The number of bouts of the postural operationalization is only 42% of the combined one and those of the intensity operationalization is about 164%. The opposite is true for the mean bout length, which was – relative to the combined operationalization – 206% in the posture operationalization and 54% in the intensity operationalization. These differences express the effect of operationalization on mean outcome measures, while the scatter plots also show a large variability. These results indicate that the type of operationalization cannot be neglected, and that it has to be considered when interpreting and comparing studies of SB research.

The effect of the type of operationalization on SB outcome measures varied, and most of these effects can be logically explained. For example, when comparing the combined operationalization with the postural operationalization, the total sedentary time will always be lower in the combined operationalization, because of the additional requirement (low intensity). In the combined operationalization, the number of sedentary bouts was higher: e.g., one bout in the postural operationalization may become two shorter bouts in the combined operationalization because of samples within that bout above the intensity threshold. When we compare the combined operationalization with the intensity operationalization there again is an additional requirement (lying or sitting), resulting in a lower total sedentary time in the combined operationalization. However, in contrast to the comparison between the combined and postural operationalization, there were less bouts in the combined operationalization when compared to the intensity operationalization. Like in the comparison of the combined and postural operationalization, intensity-based bouts of SB can be split up because of the extra (postural) requirement, which will result in more bouts in the combined operationalization. However, this effect is overruled by the effect of bouts that will be completely skipped by adding the postural requirement. Most likely this is the result of time spent standing (still). Previous research also stated that standing (still) was mostly classified as SB when using data based on movement intensity[7,9,24]. The added value of the current study, therefore, is not only to indicate that there is an effect of the operationalization of SB, but also to quantify this effect.

Accelerometers such as the Actigraph are commonly used for assessing SB, and their output in counts is comparable with our intensity operationalization. Although commonly used, this operationalization with count-based accelerometers has an important limitation. Contradictive results are found about the energy cost of standing: some studies found no difference with the energy cost of sitting, while others did find difference, although small[25-27]. Regular count-based accelerometers cannot reliably distinguish between sitting without significant movement and standing without significant movement. As a result, count-based accelerometers will probably mostly overestimate SB by measuring also some standing[6,24]. There is evidence that upper leg inclination data, which can detect body postures, have higher precision and accuracy in assessing sedentary time than accelerometers when compared to direct observation[6,9]. The most widely used example of this principle is the activPAL, which is comparable with the posture operationalization. Although this device is probably more precise in measuring sitting time, this does not mean it is more precise in measuring sedentary time. Sitting is not always sedentary; studies about energy expenditure have reported that some sitting activities exceed the sedentary threshold of 1.5 METs[27,28].

Based on the previous mentioned limitations of commonly used devices and the results of the current study, we recommend to measure both the intensity and postural component when the purpose is to quantify SB according to its formal definition; activities <1.5 METs in sitting of reclined position. It should be clear that it was not our purpose to assess the definition and the validity of its two-component character. Our study does not provide conclusions about which operationalization has, for example, the strongest relationship with health status. We are aware of the fact that the definition of SB is – so far – not strongly based on empirical studies, and that much is still uncertain about the working mechanisms of SB and about how SB contributes to health risks[29]. Therefore, it does not automatically mean that this combination of intensity and posture provides the most valid operationalization from the health perspective. Elucidating these working mechanisms will be one of the challenges of the future, and this increased knowledge will certainly affect the determination of the most reliable and valid operationalization of SB . However, based on the current definition of SB and the results of our study we suggest to measure simultaneously intensity and posture in SB research.

Some limitations of the study have to be mentioned. First of all, our intensity threshold of 0.016g was carefully determined by comparing with Actigraph, but not based on simultaneous measurement of energy expenditure. However, previous research has shown that the movement intensity time series correlated well with oxygen uptake and heart rate19. Furthermore, Boerema[30] performed a sensitivity analysis, which showed that sedentary pattern measures of daily living of office workers showed relatively low sensitivity to changes in the threshold for SB. Therefore, we think that the threshold used is reliable and small changes to a better threshold will not influence the results of our study. Another limitation is that the way we calculated intensity is different – too some extent – from other currently available accelerometers. In general, the way the body motility was calculated is quite similar to the way that movement intensity counts are calculated in other devices such as the Actigraph. However, our multi-sensor input is different from one-unit devices, and the algorithms are not exactly the same. This is a limitation, but at the same time all accelerometers have their device specific algorithms and settings, which means that comparing results of different studies always will be arbitrary[7,9].

CONCLUSION

It can be concluded that the type of operationalization of SB significantly affects SB outcome measures. To our knowledge, this is the first study quantifying this effect of operationalization. Based on these results, we recommend if measuring SB according to its formal definition of “any waking behavior characterized by an energy expenditure ≤1.5 METs and a sitting or reclining posture”, measurements must include both the intensity and posture component.

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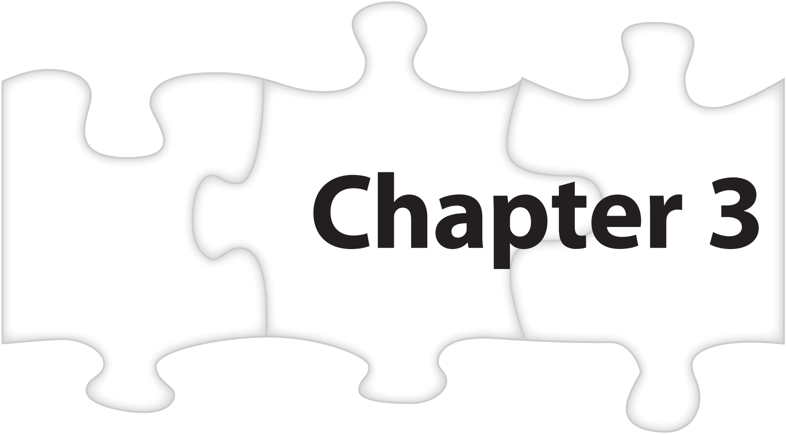

Chapter 3

Effect of different operationalizations of sedentary behavior in people with chronic stroke

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ABSTRACT

Purpose: Sedentary behavior is common in people with stroke and has devastating impact on their health. Quantifying it is important to provide people with stroke with adequate physical behavior recommendations. Sedentary behavior can be quantified in terms of posture (sitting) or intensity (low energy expenditure). We compared the effect of different operationalizations of sedentary behavior on sedentary behavior outcomes (total time; way of accumulation) in people with stroke.

Methods: Sedentary behavior was analyzed in 44 people with chronic stroke with an activity monitor that measured both body postures and movement intensity. It was operationalized as: 1) combining postural and intensity data; 2) using only postural data; 3) using only intensity data. For each operationalization we quantified a set of outcomes. Repeated measures ANOVA and Bland-Altman plots were used to compare the operationalizations.

Results: All sedentary behavior outcomes differed significantly between all operationalizations ($p<0.01$). Bland-Altman plots showed large limits of agreement for all outcomes, showing large individual differences between operationalizations.

Conclusion: Although it was neither possible nor our aim to investigate the validity of the two-component definition of sedentary behavior, our study shows that the type of operationalization of sedentary behavior significantly influences sedentary behavior outcomes in people with stroke.

INTRODUCTION

Regular physical activity contributes to primary and secondary prevention of several chronic diseases and is associated with a reduced risk of premature death[1]. Moreover, there is increasing evidence for an association between sedentary behavior (SB) and disease, health markers and mortality, independent of the level of physical activity[2-5]. SB is not the same as the lack of physical activity[6,7]; for example, during one day, individuals can be both highly active and have a large amount of SB[4,5]. The Sedentary Behavior Research Network has defined SB as “any waking behavior characterized by a low energy expenditure (≤1.5 METs) while in a sitting or reclining posture”[7]. Thus SB comprises two components: a postural one and an intensity component. Moreover, not only the amount of SB is important, but also the way in which SB time is accumulated[8,9]. For example, breaking up long periods of sedentary time may provide beneficial metabolic effects in addition to the beneficial effects of reducing total sedentary time[8,9]. Therefore, SB is expressed by several outcomes, such as total time, number of bouts, and mean bout length.

Despite the availability of a clear definition of SB[7], few studies have measured SB according to the full definition, i.e., comprising both the postural and intensity component. Some groups used an activity monitor which estimates energy expenditure[8-10] whereas others used activity monitors which measure body postures and movements (hereafter called postures/movements)[11,12]. Using only postural data, or only intensity data, as the operationalization of SB is likely to influence the values of SB outcomes. However, the effect of using these different operationalizations of SB is unknown. In order to understand how different operationalizations of SB affect SB outcomes, we previously assessed this effect in healthy people[13]. We found significant and substantial differences in SB outcomes between different operationalizations. Specifically, the amount of sedentary time differed 10-20% between different operationalizations, while the difference in the accumulation of sedentary time was even larger; i.e., fragmentation of sedentary time varied up to 50%[13]. We suggested that these differences could result from specific physical behavior patterns, such as standing still with low energy expenditure and sitting while moving with high energy expenditure[13]. Because the frequency and duration of such behaviors most likely differ between people with stroke and healthy people[14-17], the results of our previous study in healthy people may not be generalizable to people with stroke.

Measuring SB in people with stroke is relevant because of their high level of SB[14-17] and the fact the SB is a risk factor for cardiovascular diseases in persons who are already at risk[18]. Quantifying SB is important to provide people with stroke with adequate physical behavior recommendations. Previous studies on people with stroke did not measure SB according to the full two-component definition, the study was either based on estimates of energy expenditure[14,15] or on postures/movements[16,17]. Therefore, the present study aimed to quantify differences between three different operationalizations of SB in a set of SB outcomes in people with chronic stroke.

METHODS

Participants

The data of this study was collected as part of a larger study. The purpose of that larger study was to predict fall risk in daily life based on balance capacity in a group of 81 people with chronic stroke[19]. In that larger study, the level of physical activity was determined as covariate and was measured with pedometers, and in a subset of 58 participants, with a sophisticated activity monitor. Inclusion criteria were i) >6 months after a unilateral supratentorial stroke, and ii) able to stand/walk independently (Functional Ambulation Categories ≥3). Excluded were people with i) other neurological or musculoskeletal disorders affecting balance, ii) a reduced cognitive functioning (Mini Mental State Examination score <24), and iii) medication that affects reaction time. All participants provided written informed consent. The study protocol was approved by the Medical Ethics Committee of the region Arnhem-Nijmegen.

Data collection

SB was objectively measured using the accelerometer-based VitaMove activity monitor (2M Engineering, Veldhoven, The Netherlands). The VitaMove is the wireless successor of the Vitaport and both have widely been used to measure postures/movements. For detection of postures/movements, validation studies with the Vitaport were performed with video recordings as reference data, and those studies showed good results (agreement Vitaport – video around 90%) with only small differences between different patient groups (agreement ranging 87-90%)[20-22]. Thus, our measurement system has proven to be valid for postures/movements detection in a variety of populations with deviating movement patterns. In addition, the Vitaport/VitaMove system has been previously applied in people with stroke[23-27]. In addition to the valid postures/movements detection, the Vitaport/VitaMove provides reliable estimates of movement intensity and energy expenditure, comparable to those of heart rate. The way in which movement intensity is calculated is basically the same as the vector magnitude calculations in other accelerometer devices. A conceptual difference is that the Vitaport/VitaMove movement intensity (called body motility) is based on the input of 3 to 4 sensor units, whereas other accelerometer devices usually use only 1 sensor. Bussmann et al.[28] compared body motility of the Vitaport with oxygen uptake and heart rate during increasing walking speed in healthy people. Pearson correlation coefficient, based on individual linear regression equations, for the body motility – oxygen uptake relation was on average 0.97, which was the same for the heart rate – oxygen uptake relation. The inter-individual range was somewhat smaller for the body motility – oxygen uptake relation (0.95-0.98) than for the heart rate – oxygen uptake relation (0.93-0.99). Next, this body motility was used as measure for walking speed in several studies[29,30]. Finally, the body motility values showed to have a strong relationship (r=0.91) with movement counts measured with the Actigraph device[13]. We used this strong relation to set a threshold below which the intensity is defined as SB (see Data Processing). The VitaMove consists of three body-fixed accelerometers (Freescale MMA7260Q, Denver, USA), one attached to the sternum and one to each thigh. The three sensors are wirelessly connected and synchronize every 10 s; full details on this device are published elsewhere[31,32]. The system was worn during waking hours; participants fixed the sensors (using elastic belts) after getting out of bed and removed them before going to bed. Because the sensors are not waterproof, they were not worn during swimming, bathing, or showering. The monitoring period lasted for 7 consecutive days. The first day was not included in the analysis, because this was not a full and representative day: the measurement was initialized, the device was attached and the measurement instructions were given. Data was included in the analysis when the device was worn correctly for at least 3 days with a minimum of 8 h of wearing time/day. To avoid measurement bias, participants were instructed to follow their ordinary daily life; the principles of the activity monitor and the research questions were explained after the monitoring period.

Data processing

The measured accelerations were analyzed using VitaScore Software (VitaScore BV, Gemert, The Netherlands). For the postural data, the same software was used to automatically detect a specific postures/movements (lying, sitting, standing, walking, cycling, and general noncyclic movements) each second. Full details on all steps of this detection procedure are described elsewhere[31]. Briefly, the posture/movement detection is based on three feature signals that are derived from each measured acceleration signal. These feature signals are 1) an angular feature (expressing the orientation of the sensor relative to the gravity), 2) a motility feature (expressing movement intensity, based on the variability of the acceleration signal around the mean), and 3) a frequency feature (expressing the main frequency of the signal in case of repetitive movements). Based on these feature signals, posture/movement specific settings, and minimal distance-based algorithms, each second a specific posture/movement is automatically detected. One of the features used in those steps is the motility or movement intensity of each sensor, which is quantified based on the variability around the mean of the raw acceleration signal. The average of the motility of all sensors, the body motility (expressed in g: 1 g =9.81 m/s2), was used as intensity data. Comparable to other devices providing energy expenditure output (usually in movement counts), there is a threshold below which the intensity is defined as SB. In this study, a threshold of 0.045 g was used. This threshold was determined based on additional measurements in 8 healthy people (mean age 31 years; 2 men); during these measurements the participants wore the VitaMove and Actigraph (GT3X, Actigraph, Pensacola, Florida, USA), and performed a short protocol including sitting, standing and walking, all items with different intensities. The body motility of the VitaMove and the counts of the Actigraph were strongly correlated (R =0.91, p <0.001), and a VitaMove body motility of 0.045 g corresponded to 150 counts of the Actigraph, which is a valid threshold for SB[33]. After dichotomizing the body motility output, a 5-s duration threshold was applied, comparable to the post-processing of the postural data in VitaScore[31].

Sedentary behavior: operationalization and outcomes

SB was operationalized in three ways:

1. Combining postural and intensity data as the definition of SB: waking time in which i) the posture was lying or sitting, and ii) the movement intensity was low (body motility <0.045 g, comparable to Actigraph <150 counts).
2. Using only postural data: waking time in which the posture was lying or sitting.
3. Using only intensity data: waking time in which the movement intensity was low (body motility <0.045 g, comparable to Actigraph <150 counts).

For all these operationalizations SB was quantified by five SB outcomes:

1. Total time: the absolute sum of all sedentary time (in min).
2. Number of bouts: the number of uninterrupted periods of SB.
3. Mean bout length: the back transformed mean of the natural log data (in min). This transformation was done because the length of the sedentary bouts was not normally distributed.
4. Fragmentation: the number of sedentary bouts divided by the total sedentary time. The higher the fragmentation, the more fragmented the sedentary time.
5. W-index: the fraction of the total sedentary time that was accumulated in sedentary bouts longer than the median sedentary bout length. The higher the W-index, the more time is accumulated in relatively long sedentary bouts.

These outcomes were calculated by an in-house Matlab program for each measurement day, and then averaged for all days of a measurement to represent the average SB per day.

Statistical analyses

To quantify and test differences between the three operationalizations of SB, repeated measures ANOVA and Bland-Altman plots were used. For the repeated measures ANOVA the different operationalizations were used as the within-subject variable. To test sphericity, Mauchly's test was used and the Greenhouse-Geisser estimate was used when the sphericity assumption was violated. Significance level was set at $p < 0.05$ and Bonferroni's post-hoc correction was used to correct for multiple pairwise comparisons. The mean difference and corresponding 95% limits of agreement were calculated and plotted for each of the three pairs of operationalizations for all five outcomes. All analyses were performed with SPSS software version 21 and Microsoft Excel version 2010.

RESULTS

Data of 14 of the 58 participants were excluded from analysis due to system failures (e.g., low power, n=7), bad quality of data (e.g., leg sensors switched during measurement period, n=6), or too little valid data (< 3 days with at least 8 hours, n=1). Remaining data of 44 participants were included in the analysis with a mean of 5.6 days of 14 hours of measurement per participant (table 3.1).

Table 3.1 Characteristics of the participants included in the analysis (n=44)

Age in years, mean (SD)	64 (9)
Sex (male/female)	33/11
Time since stroke in months, median (25th-75th percentile)	37 (19-82)
Type of stroke (hemorrhagic/ischemic)	7/36, 1 missing
Side of stroke (left/right)	21/23
Ten-meter walking test in seconds, mean (SD)	10.8 (4.1)
Berg Balance Scale, mean (SD)	52 (7)
Timed-up-and-go test in seconds, mean (SD)	12.7 (7.4)

All SB outcomes showed a significant difference between the three operationalizations of SB (all $p < 0.001$; table 3.2 part A). The three paired t-tests of the post-hoc comparison showed that all pairs were significantly different for all SB outcomes ($p < 0.001$; $p < 0.01$ for the posture-intensity difference for the W-index; table 3.2 part B). The total time and the W-index had the highest values in the postural operationalization and the lowest in the combined operationalization, whereas the number of bouts and fragmentation had the highest values in the intensity operationalization and the lowest in the postural operationalization. The mean bout length had the opposite pattern, with the lowest values for the intensity operationalization and the highest for the postural operationalization.

Table 3.2 Part A: Mean values of the three operationalizations for all sedentary behavior outcomes and results of repeated measures ANOVA. Part B: Mean difference between the pairs of operationalizations. All differences had a p-value of < 0.001, the one marked (*) had a p-value of < 0.01.

	Total time (min)	**Number of bouts**	**Mean bout length (min)**	**Fragmentation**	**W-index**
Part A*: mean (SD)*					
Combined	494.0 (107.89)	154.3 (58.31)	86.5 (45.24)	0.341 (0.1684)	0.923 (0.0196)
Posture	572.6 (102.62)	69.3 (20.47)	151.9 (63.43)	0.131 (0.0573)	0.950 (0.0148)
Intensity	532.3 (107.45)	239.9 (61.93)	44.7 (12.06)	0.490 (0.1980)	0.938 (0.0211)
F-test, *(p-value)*	*F*(1.27, 54.59) = 111.8, *(0.000)*	*F*(1.69, 72.65) = 259.3, *(0.000)*	*F*(1.61, 69.38) = 122.4, *(0.000)*	*F*(1.35, 58.06) = 162.8, *(0.000)*	*F*(1.44, 61.75) = 40.9, *(0.000)*
Part B*:* mean difference (limits of agreement) mean difference (range between limits of agreement) in % of the mean of both operationalizations					
Combined vs. posture	-78.6 (-148.8; -8.5) -14.7% (26.3%)	85.0 (-20.8; 190.8) 76.0% (189.3%)	-65.4 (-148.4; 17.5) -54.9% (139.2%)	0.210 (-0.071; 0.490) 89.0% (237.7%)	-0.028 (-0.068; 0.012) -3.0% (8.5%)
Combined vs. intensity	-38.3 (-76.8; 0.3) -7.5% (15.0%)	-85.6 (-159.3; -11.9) -43.4% (74.8%)	41.8 (-31.7; 115.3) 63.7% (224.1%)	-0.149 (-0.298; 0.001) -35.9% (72.0%)	-0.015 (-0.042; 0.012) -1.6% (5.8%)
Posture vs. intensity	40.4 (-46.9; 127.6) 7.3% (31.6%)	-170.6 (-279.4; -61.9) -110.3% (140.7%)	107.2 (-2.0; 216.4) 109.1% (222.2%)	-0.358 (-0.676; -0.041) -115.3% (204.5%)	0.013 (-0.037; 0.062)* 1.4% (10.5%)

In the Bland-Altman plots (figure 3.1) the mean difference between the pairs of operationalizations and the limits of agreement are visualized for all SB outcomes. The mean difference in all pairs of all SB outcomes indicated a systematic difference between the operationalizations. The limits of agreement showed that there was an inter-subject variability in the difference between operationalizations. The range between the limits of agreement was larger for the outcomes describing the accumulation pattern (except for the W-index) than for the amount (total time). In figure 3.1 can also be seen that the difference between the combined operationalization and postural component alone is proportional to the magnitude of the measure for the number of bouts, the mean bout length, and the fragmentation. This also applies to the mean bout length of the other two comparisons and for the fragmentation of the posture-intensity pair.

DISCUSSION

This study compared the effect of three operationalizations of SB in a set of SB outcomes measured in people with chronic stroke. All three operationalizations yielded significantly different results for all SB outcomes. The differences between the operationalizations were systematic and showed large variability between participants.

Table 3.3 Effect of operationalization in people with stroke (present study) compared with results from our previous study in healthy people [13].

	People with stroke (present study)	**Healthy people (previous study)**
	n=44 33 males; age 64 (9) years	n=53 19 males; age 48.4 (14.6) years
Total time		
Combined	494.0 (107.89)	505.8 (113.85)
Posture	572.6 (102.62)	593.2 (112.09)
Intensity	532.3 (107.45)	565.5 (108.54)
Number of bouts		
Combined	154.3 (58.31)	204.8 (99.84)
Posture	69.3 (20.47)	86.2 (31.72)
Intensity	239.9 (61.93)	336.6 (110.75)
Mean bout length		
Combined	86.5 (45.24)	72.2 (31.68)
Posture	151.9 (63.43)	148.6 (66.73)
Intensity	44.7 (12.06)	38.9 (10.37)
Fragmentation		
Combined	0.341 (0.1684)	0.428 (0.2434)
Posture	0.131 (0.0573)	0.152 (0.0727)
Intensity	0.490 (0.1980)	0.628 (0.2712)
W-index		
Combined	0.923 (0.0196)	0.912 (0.0268)
Posture	0.950 (0.0148)	0.937 (0.0229)
Intensity	0.938 (0.0211)	0.925 (0.0267)

Total time and mean bout length is expressed in minutes.

Our results indicated systematic differences in SB outcomes between the different operationalizations of SB. Specifically, the combined operationalization yielded the lowest duration of sedentary time compared to the postural and intensity operationalizations. This difference can be logically explained by the conceptual differences between the operationalizations. Both the postural and intensity operationalization have only one requirement: either time has to be in a sitting or reclined position, or below a certain intensity level. However, in the combined operationalization both requirements must be met, which logically results in less time indicated as SB. When we compared the sedentary time in the postural operationalization to the time in the intensity operationalization we found the highest duration in the postural operationalization. This difference cannot be immediately explained from a conceptual perspective, because there are two effects that counteract each other: in the postural operationalization, some of the time will be classified as SB while this time does not meet the requirement of a low intensity, for example in the case of so-called 'active sitting'. On the other hand, in the intensity operationalization, 'standing still' might be included as SB, whereas this does not meet the postural requirement.

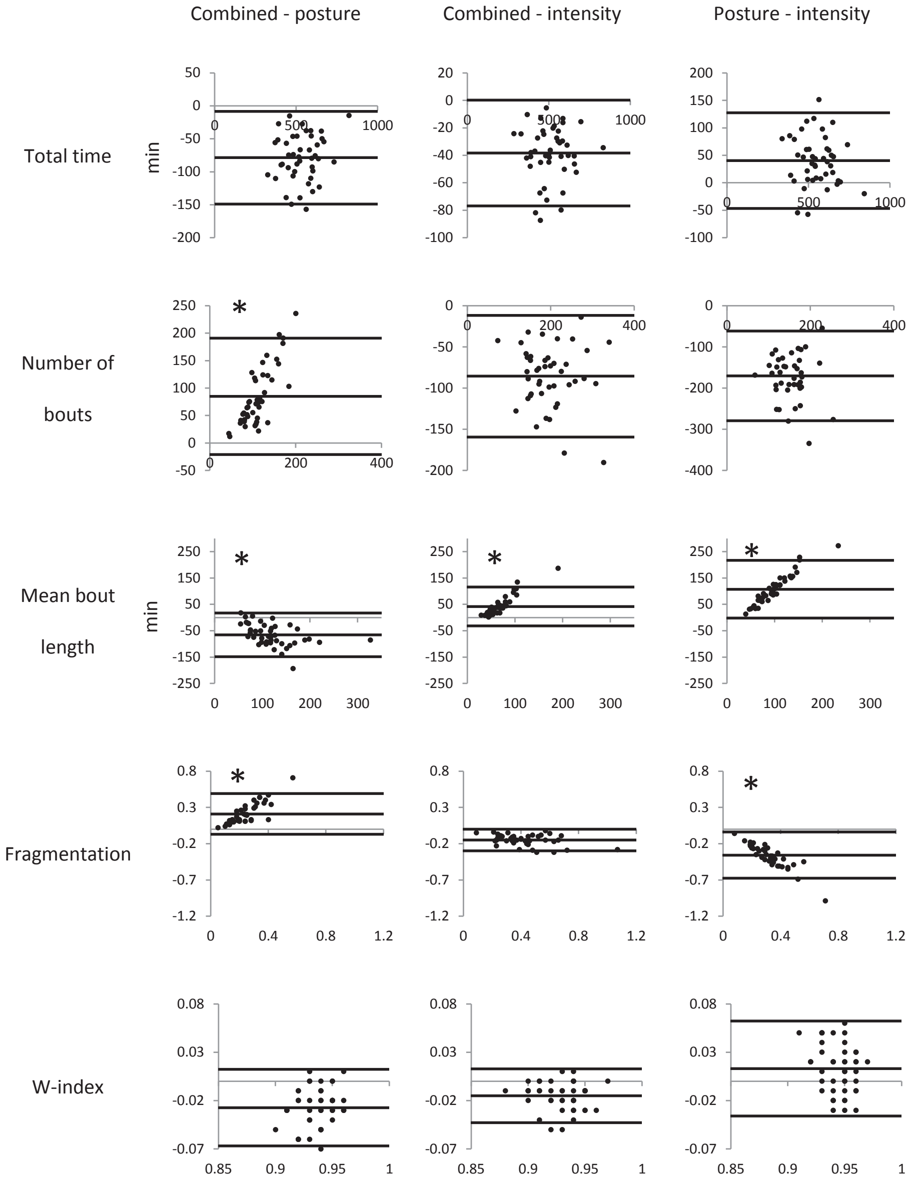

Figure 3.1 Bland-Altman plots (x-axis: mean of both operationalizations; y-axis: difference between both operationalizations) per pair of operationalization for all sedentary behavior outcomes.

The type of operationalization did not only affect the duration of SB, but also the other outcomes. For example, in the postural operationalization time classified as SB was, as already discussed, higher, but also accumulated in less bouts which were on average longer compared to the combined operationalization. The opposite happened in the intensity operationalization, with shorter time classified as SB, but accumulated in more and shorter bouts compared to the combined operationalization. The time of SB only detected by one of both requirements can be within two SB bouts connecting them to one larger bout, or can be a separate bout. These differences in SB outcomes between the operationalizations were not only significant (table 3.2, Part B), but also sufficiently large to be considered clinically relevant. Especially outcomes related to the accumulation of SB (e.g., the number of bouts, mean bout length, and fragmentation) exhibited large differences between almost all pairs of operationalizations; these differences were larger than 50% of the mean value of the compared operationalizations.

Besides large mean differences, the limits of agreement were also large (table 3.2, Part B. and figure 3.1). These large limits of agreement indicate a high variability in the individual differences between operationalizations. In some participants SB outcomes differ very little between two operationalizations, whereas others show a considerable difference between two operationalizations. However, the limits of agreement were overestimated for some comparisons (figure 3.1: indicated by *) because the difference between the two operationalizations was dependent on the mean value; i.e., when being more sedentary the two operationalizations differ more from each other. In those comparisons, the individual variability was much lower when taking dependency into account. This result was not expected and it is unclear why this occurs in only some of the SB outcomes for some pairs of operationalization. However, our main results still showed a systematic difference between the three operationalizations, with individual variability in the differences between operationalizations.

The present study is a continuation of our earlier study investigating the effect of operationalization in healthy people; the previous study revealed a strong and significant effect of the operationalization of SB in a set of SB outcomes[13]. The rationale for this additional study in people with stroke is that the previous results cannot be automatically generalized to people with stroke. In addition, we assumed that a different physical behavior might also influence the effect of the operationalization of SB, and based on literature, we also assumed that people with stroke have a different physical behavior than healthy people[14-17]. In both our studies, the same SB outcomes were calculated and the same operationalizations of SB were used. Analysis revealed that values on the SB outcomes per operationalization differed only slightly between healthy people in our earlier study and people with stroke in the present study (see table 3.3 for comparative data). However, because the healthy group differed in demographic characteristics from the stroke group, we cannot conclude that the physical behavior of healthy people and people with stroke is the same, despite the minor differences in these values. Therefore, the present study provides relevant findings, i.e., that also in people with stroke there is a strong effect of operationalization of SB on a set of SB outcomes.

The effect of operationalization is important when using SB outcomes in research or clinical practice. Operationalization of SB is mainly determined by the measurement device used. For example, Actigraph (an accelerometer commonly used to assess SB) has movement counts as primary output, which is comparable to the intensity operationalization[8-10,14], whereas activPAL (also increasingly used to assess SB) primarily measures postures/movements comparable to the postural operationalization[11,12,16,17]. When comparing the results of SB when SB has been operationalized in different ways (i.e., mainly when two different devices are used), it remains unclear whether there is a real difference in SB, or whether the difference is caused by the different operationalization of SB. Therefore, we recommend that SB data and results only be compared when both outcomes are measured with the same operationalization of SB. This applies to various types of comparisons e.g., comparing one's own results with literature, comparing different groups, and comparing longitudinal results within the same study.

Based on this study, it was neither possible nor our aim to investigate the validity of the two-component definition of SB. However, as mentioned in our previous paper, elucidating the working mechanism of SB and the most reliable and valid way to operationalize SB is the next major challenge in research[13]. Until then, we recommend to simultaneously measure postures/movements and intensity in SB research to follow the consensus definition of SB proposed by The Sedentary Behavior Research Network[7]. When both components are measured simultaneously, it is also possible to elucidate the contribution of both components separately to SB and its health effects. It is possible to measure simultaneously postural and intensity data with devices such as the Actigraph and activPAL, albeit they are not often used in that way. Some information is available on measuring postural data with the Actigraph and estimating energy expenditure with activPAL[34-37]; however, studies using these functionalities[38,39] had other aims and did not combine postural data and intensity data to estimate SB. Hopefully, those devices will be improved to enable simultaneously measuring postures/movements and intensity to estimate SB according to its definition.

A limitation of the present study is that the intensity (or energy expenditure) was measured indirectly by movement counts. Although the threshold for SB was determined previously, this was not verified with simultaneous direct measurement of energy expenditure[13]. Furthermore, this threshold was not adjusted for people with stroke relative to healthy people. Performing PA is more strenuous for people with chronic conditions than for healthy people, indicating the need to adjust thresholds for intensity levels[6]. However, adjusting the threshold for the SB level seems less urgent than for PA, due to the generally very low burdening during sedentary activities.

CONCLUSION

Although it was neither possible nor our aim to investigate the validity of the two-component definition of SB, the present study shows that the type of operationalization of SB has a significant impact on SB outcomes in people with chronic stroke. Therefore, comparing SB outcomes from different studies requires caution and should only be done when SB is operationalized in the same way.

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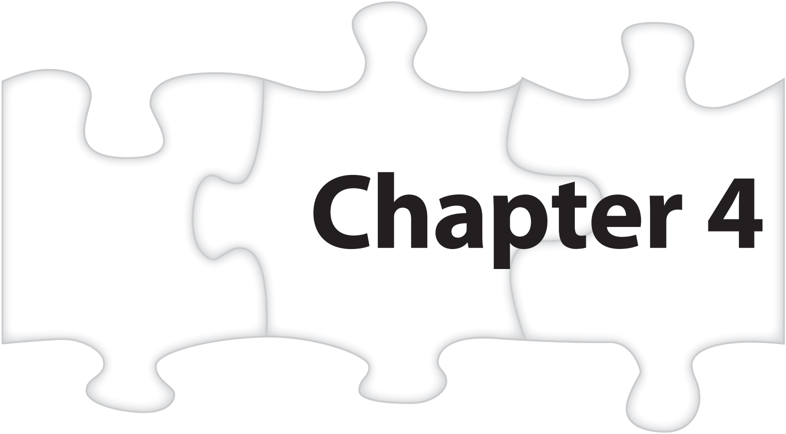

Chapter 4

The Accuracy of the Detection of Body Postures and Movements Using a Physical Activity Monitor in People after a Stroke

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ABSTRACT

Background: In stroke rehabilitation not only are the levels of physical activity important, but body postures and movements performed during one's daily-life are also important. This information is provided by a new one-sensor accelerometer that is commercially available, low-cost, and user-friendly. The present study examines the accuracy of this activity monitor (Activ8) in detecting several classes of body postures and movements in people after a stroke.

Methods: Twenty-five people after a stroke participated in an activity protocol with either basic activities or daily-life activities performed in a laboratory and/or at home. Participants wore an Activ8 on their less-affected thigh. The primary outcome was the difference in registered time for the merged class "upright position" (standing/walking/running) between the Activ8 and the video recording (the reference method). Secondary analyses focused on classes other than "upright position".

Results: The Activ8 underestimated the merged class "upright position" by 3.8% (775 s). The secondary analyses showed an overestimation of "lying/sitting" (4.5% (569 s)) and of "cycling" (6.5% (206 s)). The differences were lowest for basic activities in the laboratory and highest for daily-life activities at home.

Conclusions: The Activ8 is sufficiently accurate in detecting different classes of body postures and movements of people after a stroke during basic activities and daily-life activities in a laboratory and/or at home.

INTRODUCTION

Physical activity is an important component of physical behavior, that is, the body postures, movements and physical activities people perform in daily life [1]. Physical activity, mostly assessed as energy expenditure, has shown to be related to cardiovascular disease, cancer, obesity and fitness[2-4]. This applies not only to the general population, but also to people with a chronic condition, such as strokes[5,6].

Many studies focus on overall levels of physical activity. However, physical behavior not only involves an amount of physical activity; for example, it can be described in more detail by frequency, intensity, time and type of activity (that is, the FITT classification)[7]. In older people, it is, for many reasons, more relevant to study other aspects of physical behavior, such as postural allocation and type of activity, than the energy expenditure associated with physical activity[8]. The same reasoning applies to people after a stroke; for example, preventing too much time lying and sitting and promoting upright activities (for example, standing, walking) will prevent deconditioning of the locomotion system and benefit recovery. In other words: the difference between “sitting” and “standing” might be small from the perspective of levels of physical activity and health, but is crucial for the recovery of motor functioning. Therefore, measuring objectively and validly the type of body postures and movements (hereafter called postures/movements) as specific components of physical behavior is needed to assess the functional status and recovery, and to be able to guide and evaluate general and personalized rehabilitation interventions.

Although the number of instruments available to monitor physical behavior is increasing, most have not been validated for the use in people after a stroke. Moreover, these instruments generally focus on overall levels of physical activity or energy expenditure rather than on postures/movements[9]. The few instruments that do detect postures/movements, for example, VitaMove[10,11], PAL2[12], Dynaport MoveMonitor[13,14], and activPAL[15], are expensive and/or difficult to use in clinical practice.

The Activ8 Physical Activity Monitor (Activ8)[16] is a commercially available one-sensor accelerometer which is unique in the sense that it determines six classes of postures/movements, and energy expenditure (based on movement counts). This monitor is attractive to use in clinical practice because it is user-friendly and low-cost; moreover, it is a noninvasive, small, and lightweight one-sensor monitor. Besides measuring physical behavior, it has a feedback function on the sensor unit itself and results can be shared and discussed on an online communication platform for caregivers and consumers. The Activ8 has shown to be valid for detecting classes of postures/movements in healthy people[17]. However, before the Activ8 can be used to measure physical behavior to assess functional status and recovery in people after a stroke, a population-specific validation study has to be performed. First of all, many people after a stroke have mobility problems as well as a variety of deviating movement patterns, which may lead to misdetection of postures/movements. In addition, in stroke research and treatment, the detection of being upright versus lying or sitting is as important as detecting postures/movements in general. Therefore, the present study examines the accuracy of the Activ8 in detecting several classes of postures/movements during both basic activities and daily-life activities in people after a stroke, performed in a laboratory and/or at home.

METHODS

Participants

Between October 2015 and February 2016, eligible people after a stroke treated at Rijndam Rehabilitation (Rotterdam, The Netherlands) were invited to participate in this validation study via their physiotherapist or treating physician. For screening, the clinical expertise of the individual's physical therapist or physician was used. From the perspective of generalization of the results, the selection criteria were kept as broad as possible. Inclusion criteria were: (i) aged 18–75 years; (ii) a history of a stroke; and (iii) mobility problems caused by the stroke. Exclusion criteria were (i) mobility problems not caused by the stroke; (ii) insufficient communication skills or cognitive function to provide informed consent and/or understand the instruction; and (iii) severe mobility problems which would prevent safe participation (that is, functional ambulation category score <3[18]). We included 25 people after a stroke: 21 males and 4 females; mean age 56 (standard deviation (SD) 12) years. The mean time post-stroke was 14 (SD 13) months. Of all participants, 16 had an infarction (based on medical records) and 10 were affected on the right side of their body (this was the dominant side in 24 of the 25 participants). The median score on the Berg Balance Scale was 50 (interquartile range 11)[19] with a mean walking speed of 0.8 m/s (SD: 0.4 m/s). All participants gave written informed consent and were assured that they could not be identified via publication (that is, all data were fully anonymized). The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Medical Ethics Committee of Erasmus MC University Medical Center Rotterdam (MEC 2015-211).

Activ8

The Activ8 (Remedy Distribution Ltd., Valkenswaard, The Netherlands)[16] is a small (30 × 32 × 10 mm) and lightweight (20 g) one-sensor device that contains a triaxial accelerometer, a real-time clock, a battery, and a medium for data storage. The Activ8 determines time spent in the following six classes: "lying/sitting", "standing", "walking", "cycling", "running", and "non-wear". For the primary analyses of this study, the classes "standing", "walking" and "running" were merged into the class "upright position". In secondary analyses, "standing" and "walking" were separated, but "walking" and "running" remained merged. The detection of the Activ8 classes is based on the angular position of the sensor and the movement intensity, whereas movement intensity is based on the variability around the mean of the raw acceleration signal. The raw acceleration signals were measured and stored at 12.5 Hz and converted to postures/movements with a resolution of 1.6 Hz. Data were stored with the smallest possible epoch of 5 s, resulting in 8 non-time-stamped samples per 5 s. This characteristic allows us to define how much time a specific Activ8 class was determined in a 5-s epoch, but not (in case of two or more Activ8 classes) in which part(s) of the epoch. In the present study, the commercially available professional version was used and attached with Tegaderm™ skin tape to the front of the less-affected thigh, halfway between the hip and knee for the duration of the assessment (Figure 4.1). This is different from manufacturer's instructions to place the Activ8 in a trouser pocket. This was done because previous measurements showed that this position can be applied in a more standardized way, would improve the accuracy of detection, and because not everyone has trouser pockets. Participants reported no negative influence from the Tegaderm™ skin tape in terms of the wearing comfort of the Activ8. It is a non-allergic medical skin tape which can be used for several days without complications.

Figure 4.1 The Activ8 attached to the front of the less-affected thigh.

Protocol

Participants were assessed for maximally 1 h; during this period they performed a pre-set protocol with either basic activities or daily-life activities (Table 4.1). Basic activities included, for example, normal sitting, standing and walking, that is, activities involving one posture/movement only, whereas daily-life activities combined two postures/movements or whole-body movements, for example, vacuuming, unloading the dishwasher, getting dressed, and so forth. The assessment was performed in the laboratory of a rehabilitation center, or at home. Which protocol the participants performed was based on their individual physical ability (that is, more severely affected participants performed basic activities) and on their location (that is, inpatients were assessed at the laboratory). In addition to the pre-set protocol, participants were asked which activities they regularly perform and were not included in the protocol. Those activities were added to the pre-set protocol as the free-choice activities. For the basic activities, participants were instructed to stay as still and as comfortable as possible. The pace for comfortable over-ground walking, walking on a treadmill, and cycling was chosen by the participant, as was the pace of the slower and faster types of walking and cycling. The daily-life activities and free-choice activities were also performed in the participant's normal way and pace. During all activities, supervision was available to ensure the participant's safety; however, to enable all activities to be performed as "normally" as possible (to reflect everyday life), supervision was kept as unobtrusive as possible. Based on pragmatic reasons (for example, the physical ability of each individual) some activities were excluded from the protocol. Each activity was scheduled to last approximately 80 s. However, the duration of some activities was either shorter (for example, when the activity was quickly completed), or sometimes longer (for example, when walking or cycling outside) when

Table 4.1 The pre-set activities of the basic activities protocol and of the daily-life activities protocol.

Basic Activities Protocol	**Daily-Life Activities Protocol**
Lying (9, 7)	Sitting with upper limb activity ◊ (18, 10)
Sitting * (17, 10)	Standing with upper limb activity ◊ (13, 10)
Standing * (14, 9)	Walking while carrying an object (11, 2, 2)
Walking overground ‡ (16, 6, 3)	Hanging laundry (13, 1)
Walking on treadmill ‡ (3, 0)	Packing a bag (12, 5)
Staircase walking (6, 7)	Kitchen activities (12, 9)
Cycling ‡ (13, 3, 2)	Personal care activities (13, 1)
	Throwing a ball (8, 0)
	Vacuuming (12, 5)

*Numbers between brackets are the number of participants that performed the activity (in the laboratory, at home inside, at home outside). * indicates activities performed twice; ‡ indicates activities performed at a comfortable pace and, if possible, also at slower and faster speeds; ◊ indicates the sitting or standing body posture while performing multiple functional activities (for example, writing, eating, getting dressed).*

a participant was assessed at home or performed daily-life activities. A total assessment lasted maximally for 1 h (irrespective of the activities or location) and all participants were given the opportunity to rest between activities. All activities were recorded with a handheld digital video camera which served as the reference method. Video data were synchronized in time with the Activ8 registration.

Data analyses

To analyze the video recording, clear criteria to score the different video classes were developed, extensively discussed, and applied. To allow more insight into potential error sources, the initial video classes differed from the Activ8 classes. Ten video classes were defined: “lying”, “sitting”, “sit-to-stand transfer”, “standing”, “standing with leg movements”, “shuffling”, “walking”, “staircase walking”, “cycling”, and “running”. Each second of the video recording was assigned to one of these classes. In the case that a class was unclear, a consensus was obtained together with a second researcher. For the main analysis, some video classes were merged. For the primary analysis the following categories were merged: (i) “lying” and “sitting” (lying/sitting class); and (ii) “standing”, “standing with leg movements”, “shuffling”, “walking”, “staircase walking”, “running”, and “sit-to-stand transfer” were merged into the “upright position” class. For the secondary analyses the following categories were merged: (i) “lying” and “sitting” (lying/sitting class); (ii) “sit-to-stand transfer” and “standing” (standing class); and (iii) “shuffling”, “staircase walking”, “walking”, and “running” (walking class). The video class “standing with leg movements” was merged into the “standing” class for the basic standing activities, and into “walking” for the walking activities. For daily-life activities, generally characterized by quick alternations of standing and walking, it was found to be difficult to allocate “standing with leg movements” to the “standing” or “walking” video class. Therefore, for these activities, the secondary analyses with “standing” and “walking” separated were not performed. The entire duration of each performed activity was analyzed, except for some samples at the beginning or end when an activity started or ended within a 5-s epoch of the Activ8. Because it was not possible to determine the timing of samples within a 5-s epoch and, as a result, to calculate a 1-s agreement for activities which existed of more than one posture/movement, we compared the total duration of all classes within an activity. The primary outcome was the total difference in time between the Activ8 and the video recording for the class “upright position” (standing/walking/running) presented for all data together (overall data) and for the basic activities and daily-life activities in the laboratory and at home separately. Secondarily, we focused on the total time differences between the Activ8 and the video recording for the two components of “upright position” (the classes standing and walking/running) and for the classes other than “upright position”. The total time difference was defined as the total time of a posture/movement measured by the Activ8 minus the actual time of that posture/movement according to the video recording. This difference was expressed as percentages as well by dividing it by the actual time according to the video recording. We defined a total time difference of 10% as acceptable for both the basic activities and daily-life activities. We used a percentage of 10% because a previous developed activity monitor detecting postures/movements had comparable accuracy and provided meaningful outcomes in previous research[20,21]. Next to the total time difference, the agreement between the Activ8 and the video recording was calculated and defined as the time of a posture/movement correctly classified by the Activ8. To visualize the individual differences in the total time difference, Bland–Altman plots were made. For the classes "upright position", "lying/sitting", and "cycling" all the data were used (that is, basic and daily-life activities in the laboratory and at home), whereas, for the classes "standing" and "walking/running", only data from the basic activities (performed in the laboratory or at home) were used. The reason for this was the described issue of not being able to validly allocate the video class "standing with leg movements" to the "standing" or "walking" video class during daily-life activities. However, to give some insight into the classification of standing and walking during daily-life activities, some exemplary data will be provided per daily-life activity.

RESULTS

A total of 25 participants were included in this study. Eight of these participants were willing to participate in a second assessment to either perform other activities (basic and daily-life activities) or to perform activities at a different location (laboratory/home). Table 4.1 presents the number of unique participants included per activity in each of the locations (numbers between brackets). The large differences in the number of participants per activity are due to the ability of the participants; the availability of a bed, staircase, bike, and so forth; and/or due to limited time.

"Upright position"

The main results are presented in Table 4.2. Overall, the Activ8 underestimated the class "upright position" (difference Activ8 versus video −3.8%), ranging from −0.5 to −7.0% for the different activity protocols at the different locations. Figure 4.2 shows that the total difference between the Activ8 and the video recording was due to differences in about half of the participants of which in most of them "upright position" was underestimated. The agreement between the Activ8 and the video recording ranged from 82.2 to 97.6%.

Components of "upright position"

In the basic activities, analysis of the components of "upright position" shows that the Activ8 overestimated the class "standing" (difference Activ8 versus video: laboratory

Table 4.2 The video data, Activ8 output, time difference (absolute in seconds and as a percentage), and agreement (overall and per protocol).

		Video (s)	Activ8 (s)	Time Diff (s) *	Time Diff (%)	Agreement (%)
Overall	Upright	20,239	19,464	–775	–3.8	92.6
	Lying/sitting	12,754	13,323	569	4.5	95.3
	Cycling	3163	3369	206	6.5	99.4
Basic activities in laboratory	Upright	5651	5624	–27	–0.5	97.6
	Standing	*1827*	*2088*	*261*	*14.3*	*95.9*
	Walking/running	*3824*	*3536*	*–288*	*–7.5*	*91.5*
	Lying/sitting	3407	3411	4	0.1	97.9
	Cycling	2426	2449	23	1.0	98.6
Basic activities at home	Upright	2967	2878	–89	–3.0	92.9
	Standing	*1257*	*1273*	*16*	*1.3*	*89.7*
	Walking/running	*1710*	*1605*	*–105*	*–6.1*	*90.4*
	Lying/sitting	2631	2588	–43	–1.6	96.4
	Cycling	737	869	132	17.9	100
Daily activities in laboratory ‡	Upright	6984	6648	–336	–4.8	95.2
	Lying/sitting	3548	3856	308	8.7	87.9
	Cycling	0	28	28	N/A	N/A
Daily activities at home ‡	Upright	4637	4314	–323	–7.0	82.2
	Lying/sitting	3168	3468	300	9.5	100
	Cycling	0	23	23	N/A	N/A

*Time Diff = Time Difference, * Calculated as Activ8 minus video recording. Negative value: Activ8 underestimates, positive value: Activ8 overestimates. ‡ In daily life activities, the "upright position" was not subdivided into the classes "standing" and "walking/running", because of the aforementioned issue of not being able to validly allocate the video class "standing with leg movements" to the "standing" or "walking" video class during daily-life activities.*

14.3%; home 1.3%) and underestimated the class "walking/running" (difference Activ8 versus video: laboratory –7.5%; home –6.1%) (Table 4.2). The variability in the individual differences between the Activ8 and the video recording for "standing" was due to differences in about half of the participants, although dominated by four participants. For "walking/running", more participants had a difference between the Activ8 and the video recording, but it was here dominated by four participants as well, of which three were the same as those for "standing". Table 4.3 (part A) shows the classification of the Activ8 and of the video recording for a part of the daily-life activities in the laboratory. The video class "standing with leg movements" was more or less equal to the difference between the Activ8 classification and the video classification of the class "walking".

Other postures/movements and free-choice activities

Overall, the Activ8 overestimated the duration of “lying/sitting” by 4.5%, resulting from

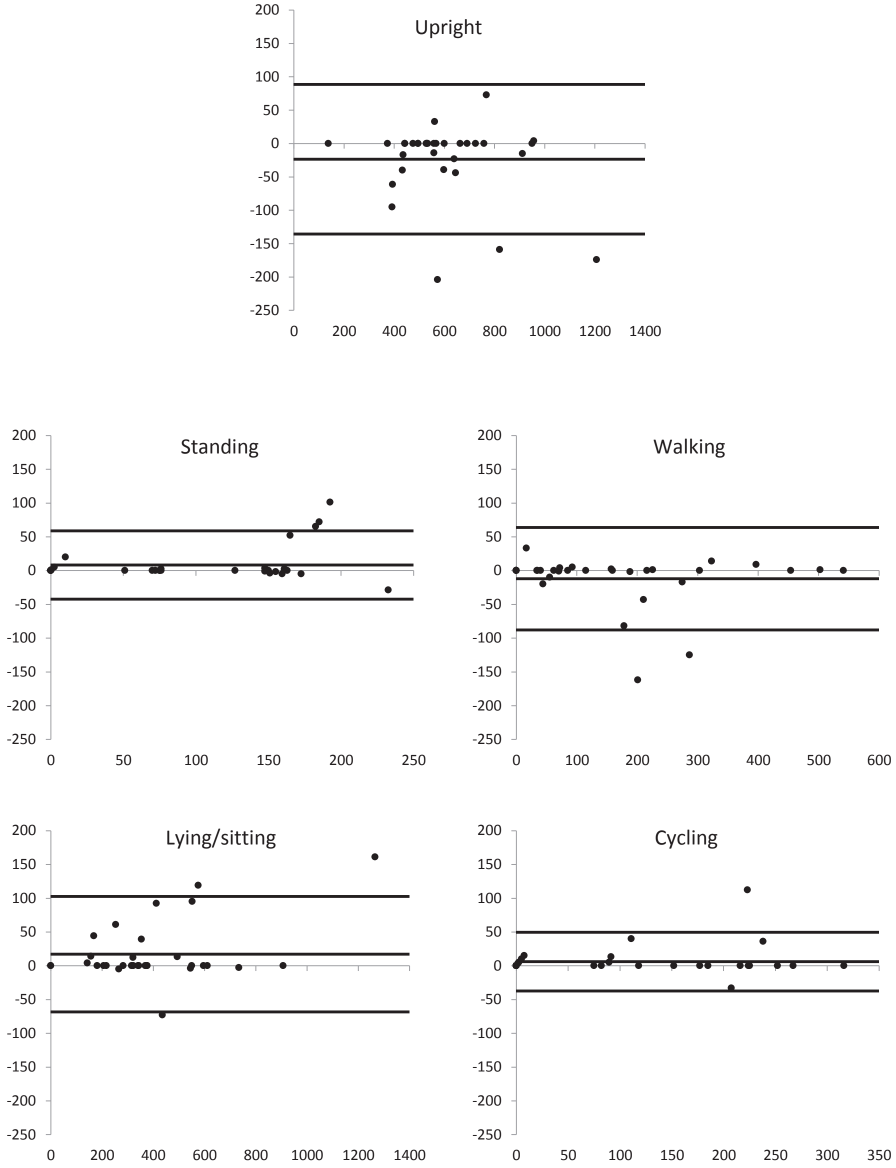

Figure 4.2 The Bland–Altman plots (x-axis: mean of Activ8 and video recording; y-axis: difference, calculated as Activ8 minus video recording) of the body postures and movements for all data together. The solid lines are the mean difference and the upper and lower limits of agreement. For “standing” and “walking/running”, only data from the basic activities (performed in the laboratory or at home) were used. Each dot is one assessment.

differences in about half of the participants of which in most of them "lying/sitting" was overestimated. For "cycling", the overestimation was 6.5%, half of this difference was caused by one participant (Table 4.2; Figure 4.2). Results of the free-choice activities are presented in Table 4.3 (part B). At the laboratory, six participants performed the activity in which they propelled a wheelchair with their leg. This was detected by the Activ8 as both "sitting" and "cycling". One participant had a stair lift at home and the use of this was detected almost entirely as "sitting". Another participant performed fitness activities on a daily basis at home, for example, stepping up/down on the stairs, and squatting activities; both of these activities were mainly detected as "walking".

Table 4.3 The registered video and the Activ8 time of daily-life activities (Part A) and free-choice activities (Part B).

Activity	Total (s)	Postures/Movements	Video (s)	Activ8 (s)
Part A				
Hanging laundry	1078	Sitting	0	53
		Standing	865	873
		Standing while moving legs	209	0
		Walking	4	152
Kitchen activities	1707	Sitting	259	256
		Standing	1065	954
		Standing while moving legs	332	0
		Walking	51	494
		Cycling	0	3
Throwing a ball	593	Sitting	75	75
		Standing	455	414
		Standing while moving legs	51	0
		Walking	12	104
Vacuuming	829	Sitting	0	29
		Standing	369	375
		Standing while moving legs	456	0
		Walking	4	425
Part B				
Wheelchair driving with leg propulsion	646	Sitting	646	196
		Cycling	0	450
Fitness activities	23	Standing	16	2
		Standing while moving legs	4	0
		Walking	3	21
Using a stair lift	192	Sitting	192	192

DISCUSSION

The aim of the present study was to determine the accuracy of the Activ8 to detect several classes of postures/movements in people after a stroke while performing different pre-set activities in a laboratory or at home. A small overall difference in time was found between the Activ8 and the video recording for the main outcome class "upright position". The difference was smallest for basic activities performed in the laboratory and largest for daily-life activities performed at home. However, this was expected because of the more variation in postures/movements, that is, these are more natural, fluent, and adapted to the activity and environment during daily-life activities and at home. The findings of this study indicate that the Activ8 yields valid measurements of several classes of postures/movements in daily life in people who have suffered a stroke.

Although the "upright position" was generally well detected, it was slightly underestimated by the Activ8: in eight participants, standing (for a shorter or longer period) was classified as "sitting", and in six, partly the same, participants some walking time was classified as "cycling". All outliers in the plot of "upright position", "lying/sitting", and "cycling" of Figure 4.2 were part of these participants. This misdetection occurred mainly in participants who stood or walked with flexed hips and, hence, whose thigh was less vertical during these activities. This misdetection is, at least partly, the result of our positioning of the Activ8, that is, we attached the device to the front of the thigh in order to standardize the measurements and avoid non-wear when applied in daily-life measurements. Initially, however, the device was developed to be carried in a trouser pocket, and the signal processing and settings were optimized for this situation. In a previous study, however, the results were more reliable when the device was fixed to the thigh instead of using the trouser pocket[17]. That previous study was performed in healthy people who did not stand or walk with flexed hips. After all these measurements, the manufacturer made it possible to select the sensor location when initializing a measurement, which allows measuring with slightly different settings in the algorithm when the sensor is attached to the thigh, which will lower the above-mentioned errors.

To obtain more insight into the accuracy of the detection of the class "upright position", its two components "standing" and "walking/running" were examined separately as well. During basic activities, both in the laboratory and at home, the overall standing time was overestimated and the walking time was underestimated. The Activ8 determines the distinction between "standing" and "walking" by a threshold applied to the variability in the acceleration signal, which represents the intensity of the movement. Three participants had a very low walking speed and step frequency (0.14–0.36 m/s; 14–24 steps/min), and the movement intensity of their walking was below the threshold for "walking". Two of these participants were an outlier of Figure 4.2. As a result, for those who walk very slowly after the stroke, the Activ8 may not be sufficiently accurate to detect walking. A lower intensity threshold for walking might solve this issue. However, in daily-life activities, the video class "standing with leg movements" seemed to be classified as walking by the Activ8. Although it is debatable whether this is good or not because the leg movement was sometimes very minor, lowering the intensity threshold would also increase classifying such minor leg movements as walking. Overall, it can be concluded that the Activ8 validly detects that someone is in an upright position and that the Activ8 can be used for that during rehabilitation of people after a stroke to assess the functional status and recovery. However, for the distinction between standing and walking, some validity issues remain.

The free-choice activities were included to get an indication of the Activ8 output during "other" activities. One activity was "leg propulsion of a wheelchair"; this was selected because this is a common way for people after a stroke to move around during rehabilitation. In the present study, this activity was classified as "cycling" almost 70% of the time. This misclassification is understandable because the wheelchair driver propels the wheelchair in a sitting position, moving the legs in a way similar to that when cycling. From an energy expenditure perspective, it is debatable whether this misclassification is a problem. However, it does mean that it is difficult to distinguish between actual cycling (for example, on a home trainer during therapy) and propelling a wheelchair with the legs, which could be important when measuring physical behavior during rehabilitation after a stroke. Therefore, it might be helpful to use an additional "short and simple" activity log book.

Overall, the results provided by the Activ8 in people after a stroke were similar to those acquired with the Activ8 in healthy subjects[17] and with the few other activity monitors measuring postures/movements that have been validated for people after a stroke, such as PAL 2[12] and activPAL[22]. The latter device has also been tested in slow walking people after a stroke, and also showed a decrease in accuracy for walking speeds lower than 0.4 m/s (0.39 to 0.2 m/s: ±70% accuracy; <0.19 m/s: ±55% accuracy)[23]. However, comparing devices on the basis of the literature requires caution due to differences between the studies in terms of activity protocols and study design. Although we realize that other instruments can be used to measure physical behavior in people after a stroke, some important points need to be considered. First, most devices provide overall physical activity data (movement counts, energy expenditure), but no information about postures/movements. Secondly, very few instruments have been validated in people after a stroke. Due to possible changed movement patterns, valid results in healthy people or other patient groups cannot be automatically extrapolated to the stroke population.

Together with the ability to give real-time feedback, we believe that the Activ8 has the potential to have additional scientific, practical, and clinical value.

Study limitations

The present study has some limitations. First, the total number of samples analyzed was not large due to both the protocol (that is, a selection of representative daily-life activities of short duration) and the participants (that is, not all were able to perform all the pre-set activities). Secondly, it was, unfortunately, not possible to calculate a 1-s agreement for activities which existed of more than one posture/movement. The smallest possible interval is a 5-s epoch, in which it was not possible to determine the timing of the samples. Although the broad inclusion criteria might be a limitation as well, a broad range of severity was allowed to optimize the generalization of the results. Moreover, a brief analysis of the results of less severely/more severely affected participants gave no indication that any differences arose related to the accuracy of the Activ8. In future research, to increase ecological validity, activities should be self-chosen by the patient in a free-living environment and not be imposed by a pre-set activity protocol.

CONCLUSION

The Activ8 Physical Activity Monitor can be used to measure physical behavior during rehabilitation after a stroke. It detects the class “upright position”, “lying/sitting” and “cycling” in a sufficiently accurate way during basic activities and daily-life activities performed in a laboratory or at home. The components of the class “upright position”, that is, “standing” and “walking/running”, were detected with sufficient accuracy during basic activities. The detection of these components during daily-life activities needs further study.

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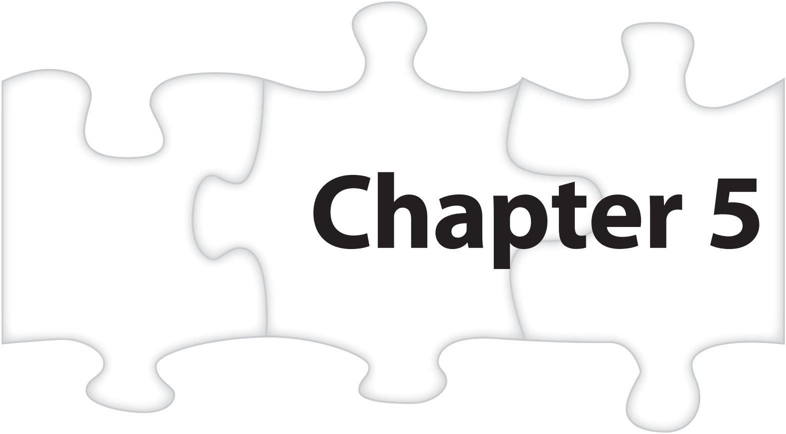

Chapter 5

Development and validation of a clinically applicable arm use monitor for people after stroke

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ABSTRACT

Objective: Developing and validating a clinically applicable and easy-to-use accelerometry-based device to measure arm use in people after stroke, i.e., the Activ8 arm use monitor (Activ8-AUM).

Design: Development and validation study.

Patients: Included were 25 people after stroke at different stages of rehabilitation.

Methods: The Activ8-AUM consists of three single-sensor Activ8s: one on the unaffected thigh and one on each wrist. Arm use was calculated by combining movement intensity of the arms with data from body postures and movements from the leg sensor. Data were divided into two sets: one for determining situation-specific movement intensity thresholds for arm use, and the other to validate the Activ8-AUM using video recordings.

Results: Overall agreement between the Activ8-AUM and video recordings was 75%, sensitivity was 73% and specificity was 77%. The agreement between the different categories of arm use ranged from 93-42% for the affected arm and from 82-24% for the unaffected arm.

Conclusion: By combining the movement intensity threshold with body postures and movements, good agreement was reached between the Activ8-AUM and video. This result, together with the easy-to-use configuration, makes the Activ8-AUM a promising device to measure arm use in people after stroke.

BACKGROUND

After stroke, about 75% of the survivors suffer from impairments of the arm, such as paralysis[1]. These impairments often result in limitations in daily life activities, greater dependency, and restrictions in social participation[2]. Limitations in daily life activities can be due to reduced performance of the arm which, in turn, can be the result of decreased capacity. However, the reduced performance can also be a result of other factors, leading to a discrepancy between what people can do (capacity) and what they actually do (performance), and in a weak or absent relationship between capacity and performance[3-5]. This so-called non-use of the affected arm is an important topic in stroke rehabilitation[6]. Therefore, besides measuring arm capacity with existing clinical measures, arm use needs to be measured too. Objectively measured arm use can be used to evaluate the effect of rehabilitation, and also during rehabilitation for coaching and feedback to stimulate arm use and personalize treatment.

Accelerometry has been introduced as an objective method to measure arm use in people after stroke[7-11]. This technique is at the moment the only one which objectively measures long periods of time to be able to measure behavior in daily life. Wrist-worn accelerometers measure arm movement and can provide a measure of arm use. However, use of accelerometry to measure arm use has specific challenges, particularly regarding sensitivity and specificity: e.g., to what extent does the device accurately determine periods of arm use when measuring arm movements. Some types of arm use (e.g., holding a cup of coffee) are associated with as little movement as possible. In addition, not all movements are necessarily related to arm use, e.g., arm movements measured during walking and during other whole body movements are functionally different from arm movements during sitting or standing. This latter issue, in which arm use is generally overestimated, has been recognized in other studies. For example, Uswatte et al.[12] used the ratio of the affected and unaffected arm, assuming that movements during walking and whole body movements affect both arms equally ; this notion has also been applied by others[10,11,13]. However, being able to remove arm movements due to walking would be a more reliable method to overcome this source of overestimating arm use. Therefore, our group developed and validated a device (the Vitaport ULAM[14]) which combines the movement intensity of the arms with data on body postures and movements (hereafter called 'postures/movements'). This additional information allows to detect walking and, based on this information, separate arm movement during walking from arm use. Rand & Eng[15,16] also used such a configuration to eliminate activity counts of arm swing while walking.

However, our previously developed Vitaport ULAM is an expensive multi-sensor system; moreover, because it is not user-friendly for patients to wear, and for therapists to analyze the data, it is not practical for use in daily life. To overcome these issues, but to still objectively measure arm use combined with postures/movements in daily life, a new clinically applicable and easy-to-use arm use monitor is required. In a previous study, we showed that measuring postures/movements in people after stroke with the Activ8 Physical Activity Monitor (Activ8) resulted in an accuracy of > 95% for the 'upright position' and of > 90% for 'lying/sitting and bicycling'[1]. The Activ8 is a simple one-sensor and low-cost accelerometer that is suitable for use in daily life[17]. For the present study we used the functionality of the existing Activ8, placed on the front of the unaffected thigh, and combined that with two additional Activ8s, one on each arm; this new configuration was called the 'Activ8 arm use monitor' (Activ8-AUM). The aims of the present study were to develop an algorithm to detect arm use using the Activ8-AUM, and to assess the validity of this new device and algorithm to detect arm use in people after stroke.

METHODS

Participants

In the present study we included people after stroke suffering from mobility problems in the arm, the leg or both and aged between 18 and 75 years. People after stroke were excluded when mobility problems were not caused by the stroke, or when they had insufficient communication skills or cognitive function to understand instructions. To guarantee safe participation, people after stroke with a functional ambulation category score <3[18] were also excluded. Between October 2015 and February 2016, eligible people after stroke were recruited via their physiotherapist or were approached by letter via their treating physician. For screening, the clinical expertise of the individual's physical therapist or physician was used. All participants provided written informed consent. The study was approved by the Medical Ethics Committee of Erasmus MC University Medical Center Rotterdam (MEC 2015-211). We were able to included 25 people after stroke: 22 males and 3 females, mean age of 56 (SD 12) years. These participants had a mean post stroke time of 15 (SD 14) months; 10 participants suffered from a hemorrhage stroke, and 11 were affected on the right side. Arm function was measured with the Frenchay Arm Test (scores 0-5, with higher scores indicating better function)[19]: 14 participants had a score of 0 or 1, 1 participant had a score of 2, and 10 participants had a score of 4 or 5.

Classification of arm use

For this study, the theoretical starting point was the framework for arm use as defined by Schasfoort et al.[20]. According to this framework, arm use is defined as 'active movement

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[1] Fanchamps et al. The Accuracy of the Detection of Body Postures and Movements Using a Physical Activity Monitor in People after a Stroke

of parts of the arm, holding objects or leaning' (Figure 5.1). This framework also shows that arm use is conceptually not the same as arm movement, and reveals the challenges and limitations of measuring arm use with accelerometry. For example, arm use can occur without much movement (e.g., when holding a cup of coffee; Figure 5.1, class 1). On the other hand, arm movement is not necessarily related to arm use, e.g., arm movements that are primarily the result of whole-body movements, such as changing sitting posture (Figure 5.1, class 4). In the framework of Schasfoort et al.[20], arm movement during walking is considered to be secondary use. In the present study, we focus only on primary use, assuming that this occurs only during sitting or standing. Therefore, analyzing arm data during walking was beyond the scope of this study.

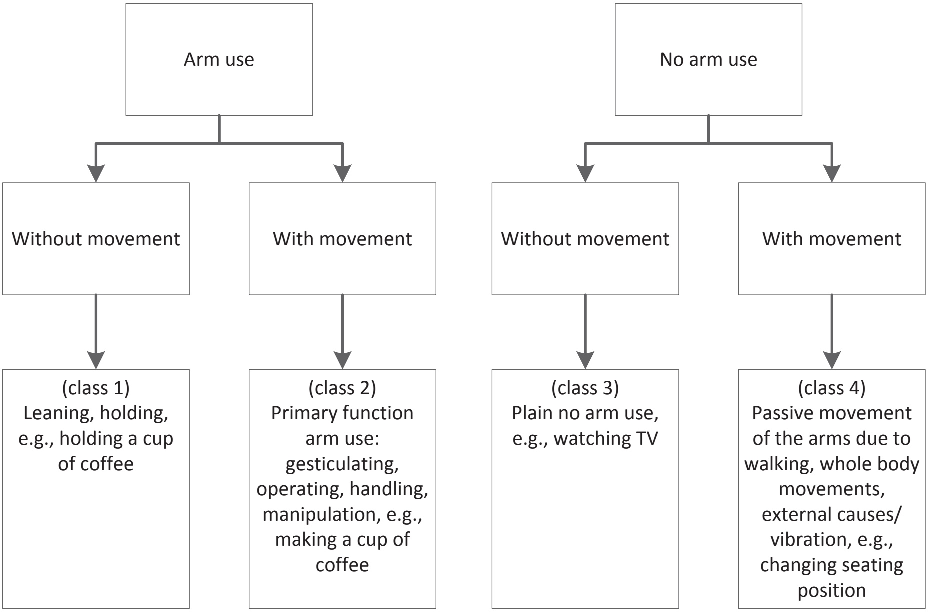

Figure 5.1 Different classes of arm use showing the relation between use and movement.

Measurement protocol

We designed a measurement protocol (Table 5.1) that included activities mainly encompassing one of the first three classes of Figure 5.1. Although no activities with class 4 as a major part of the activity were included, this class was expected to occur during other activities. Measurements were performed at a rehabilitation clinic or at the participant's home. Each specific activity lasted approximately 80 s; however, especially at the participant's home and during complex activities with arm task, the duration of some activities could be shorter (e.g., if the activity was completed) or longer (e.g., kitchen activities). The total protocol lasted maximally 1 h (including rests between activities).

Table 5.1 Activities of daily life included in the measurement protocol.

Activities including arm use, but without arm movement (class 1)	Activities including arm use, and with arm movement (class 2)	Activities including no arm use, and without arm movement (class 3)	Activities including no arm use, but with arm movement (class 4)
Sitting with a static arm task ‡	Sitting with a dynamic arm task ‡	Lying without an arm task	No tasks included
Standing with a static arm task ‡	Standing with a dynamic arm task ‡	Sitting without an arm task *	
	Personal care activities	Standing without an arm task *	
	Vacuuming		
	Hanging laundry		
	Packing a bag		
	Kitchen activities		
	Throwing a ball		

** these activities were performed twice; ‡ these activities were performed combined with multiple functional upper limb tasks (e.g., holding/reading a paper, writing, eating, and getting dressed).*

During lying, sitting, and standing without arm task, participants were instructed to be as still and as comfortable as possible. During all other activities, they were instructed to perform the activity at a comfortable, self-selected pace and using their own movement strategy. Any activities that appeared to be too difficult for an individual were excluded from the protocol. For safety reasons, participants stated their own physical limits and supervision was available during all measurements. However, to ensure that activities were performed as 'normally' as possible (to reflect everyday life), the supervision was kept as unobtrusive as possible.

Activ8 arm use monitor (Activ8-AUM)

The Activ8-AUM consists of three Activ8s (2M Engineering, Valkenswaard, The Netherlands)[17]: one Activ8 on the front of the unaffected thigh, and the others on each wrist (Figure 5.2). All sensors are easy to attach: those on the wrists are worn dorsally (like a watch) and attached with a wristband. The one on the leg is attached (with skin tape while sitting) to the front of the leg approximately halfway between hip and knee. The concept of the Activ8-AUM is similar to that of the Vitaport ULAM used by Schasfoort et al.[14], which has sensors on the wrists, chest and legs, and combines the movement intensity of the arms with data on postures/movements to calculate arm use.

The Activ8 contains a triaxial piezoelectric crystal accelerometer and was originally designed as a one-sensor device to wear on the leg or in a trouser pocket. It measures postures/movements (lying/sitting, standing, walking, cycling, running, and non-wear) as well as their movement intensity (expressed in the arbitrary unit movement counts).

Figure 5.2 Placement of the three Activ8s of the Activ8-AUM device.

Detection of postures/movements is based on the angular position of the sensor and the movement intensity, whereas movement intensity is based on the variability around the mean of the raw acceleration signal. Raw acceleration signals are measured at 12.5 Hz and converted to postures/movements with a resolution of 1.6 Hz. Data were stored with the smallest possible epoch of 5 s, resulting in eight samples for the postures/movements per epoch. For each epoch the movement counts are calculated per detected postures/movements. The internal clock used a 32kHz watch crystal (20ppm), resulting in a max clock drift of 2 s per 24 h. To be able to measure arm use, two additional Activ8s were used (one on each wrist). In the analyses, only the movement intensity data from these two sensors were used. For this, the movement counts of the detected postures/movements were summed per wrist sensor to one value for each 5-s epoch per arm, representing the total movement intensity of that arm during those 5 s. Therefore, the smallest unit in which the data could be analyzed was an entire epoch of 5s.

Video recording as reference method

A handheld digital video camera was used to record all activities; this served as the reference method. Each second of the video was classified based on the classes described in Figure 5.1: 1) arm use without movement, 2) arm use with movement, 3) no arm use without movement, and 4) no arm use with movement. To do this, criteria for the different classes were developed, extensively discussed and tested. Arm use was defined as voluntary, purposeful activity of the arm, related to active movement of the arm, or holding objects or leaning. Movement was defined as at least an observable movement of the wrist with a minimal duration of 1 s; this meant that a minor finger movement or a movement lasting only a fraction of one second was not assigned as movement. These two definitions were combined to classify the four classes mentioned above. If a classification showed to be ambiguous, a second researcher was asked to analyze this part of the measurement. In cases of no agreement a third observer was involved. Both arms were scored separately, because the classification of both arms was not necessarily the same during 1 s. Thereafter, the 1-s four-class classification was converted to a 5-s two-class classification to be comparable to the 5-s dichotomous output of the Activ8-AUM, i.e., arm use and no arm use. First, class 1 and 2 of the 1-s classification were recoded to arm use and class 3 and 4 were recoded to no arm use. Then, the majority of the samples within an epoch determined the classification for the entire epoch, either as arm use or no arm use.

Data analysis

As mentioned, the Activ8-AUM combines the movement intensity of the arms with data on postures/movements from the leg sensor. The Activ8-AUM is based on the assumptions that 1) arm use only occurs during sitting and standing, and 2) that arm use is associated with a movement intensity above a certain level. The second assumption requires defining an optimal movement intensity threshold. To do this, half of the data were selected as a development dataset, and the other half was used to validate the Activ8-AUM. The detection of postures/movements and calculation of the movement counts was done with the standard Activ8 software. These data were the input for an in-house MATLAB program detecting arm use.

Development of the Activ8-AUM

First, the data on postures/movements from the leg sensor were combined and time-synchronized with the data on movement intensity of the arm sensors and with the video data. Synchronization of the sensors was based on the time stamps within the data files using the 'synchronize' function of Matlab. The second step was selecting epochs of lying/sitting and standing, based on the postures/movements data from the leg sensor. An epoch was selected as lying/sitting when at least 5/8 samples within the 5-s epoch were determined as lying/sitting. The same holds for standing, when at least 5/8 samples had to be determined as standing for an epoch to be selected as standing. To fulfill the second assumption of the Activ8-AUM mentioned before, in the development dataset four movement intensity thresholds were determined: for the situation (A) unaffected arm during lying/sitting; (B) affected arm during lying/sitting; (C) unaffected arm during standing; (D) affected arm during standing. Although the protocol was carefully composed, such an imposed protocol probably has a different ratio of arm use and no arm use than the ratio in daily life. This different ratio might affect the optimal movement intensity threshold. Therefore, our data were adjusted to create a ratio comparable to that earlier established in the daily life of people after stroke[6]. To establish the optimal movement intensity threshold for each of the four situations mentioned above (A-D), thresholds were systematically changed between 1 and 40 movement counts, in steps of 1. Within each of the four situation, arm use was determined based on all possible thresholds (0/1, no arm use/arm use) and was compared to the two-class classification of arm use according to the video data. To determine the accuracy of each threshold per situation, the Youden's index[21] was calculated.

Youden's index = sensitivity + specificity − 100

In this, sensitivity was defined as:

$$\frac{\textit{number of samples the Activ8-AUM correctly determined as arm use}}{\textit{number of total samples of arm use}} \times 100\%$$

and specificity was defined as:

$$\frac{\textit{number of samples the Activ8-AUM correctly determined as no arm use}}{\textit{number of total samples of arm use}} \times 100\%$$

Per situation mentioned above (A-D), the movement intensity threshold with the highest Youden's index was chosen to be the value for the movement intensity above which an epoch is classified as arm use.

$$\frac{\textit{number of samples correctly determined as arm use + correctly determined as no arm use}}{\textit{total number of sample}} \times 100\%$$

Validation of the Activ8-AUM

To validate the Activ8-AUM we applied the optimal movement intensity thresholds, determined in the development dataset, to the validation dataset. Again, arm use according to the Activ8-AUM was compared to arm use according to the video data (both dichotomous measures: arm use/no arm use). Then, sensitivity, specificity, and agreement were calculated overall and for different groupings of the data: per limb, per class of Figure 5.1, and per activity of the protocol. Agreement was defined as:

$$\frac{\textit{number of samples correctly determined as arm use + correctly determined as no arm use}}{\textit{total number of sample}} \times 100\%$$

When calculating the outcomes per activity of the protocol, there was no arm use expected in activities without arm task, like only arm use was expected in activities with arm task. However, since the video recordings were used as golden standard, it might be possible that some arm use appeared in tasks without arm task and sometimes no arm use was performed in activities with arm tasks. Therefore, both sensitivity and specificity were calculated per task, provided that arm use or no arm use sufficiently appeared, i.e. at least more than 60 s (=12 5-s epochs).

RESULTS

Participants

Six participants (relatively early after their stroke onset) who were unable to perform all the activities in a first session, agreed to participate in an additional session later on during rehabilitation; for these participants, both sessions were used for the analysis. The total group of 31 measurements was divided into two datasets; a development dataset with 16 measurements and a validation dataset with 15 measurements.

Development of the Activ8-AUM

Figure 5.3 presents the movement counts for different activities of the development dataset. For both the affected and unaffected arm, the median movement counts of activities without arm task were low compared to those with arm task, indicating that a threshold could be set for discriminating between these two. However, the interquartile range was relatively large for all activities, indicating that the intensity of arm use and no arm use differed between and within participants, and that an overlap in movement counts existed between arm use and no arm use. For the affected arm, median movement counts were smaller than for the unaffected arm, with the largest difference during standing.

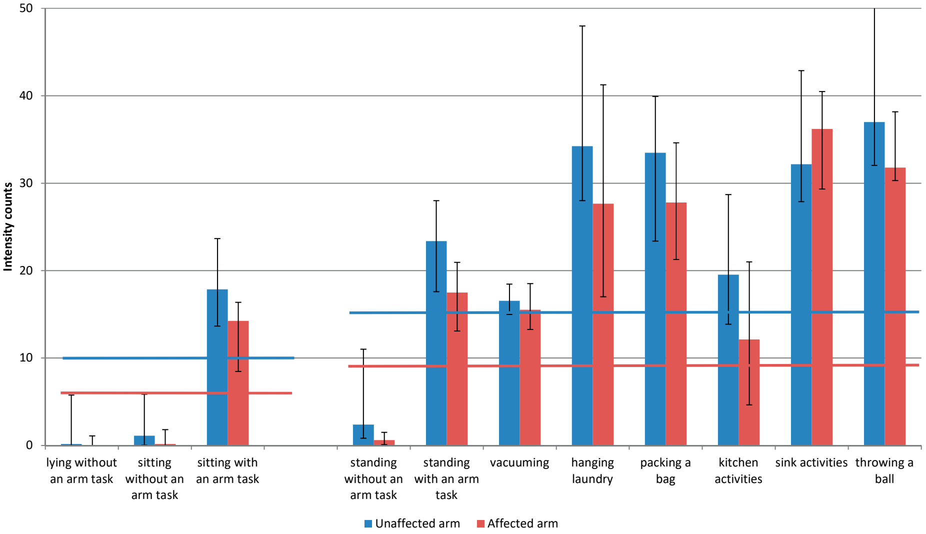

Figure 5.3 Median movement counts (25th to 75th percentile) per activity for the unaffected and affected arm.

The first three activities are subcategories of lying/sitting, the remainder are subcategories of standing. Horizontal lines indicate the movement intensity thresholds above which an epoch is classified as arm use (black for the unaffected and grey for the affected arm). The 75th percentile for throwing a ball with the unaffected arm was 94 counts.

The overlap in movement counts between arm use and no arm use showed that it was not possible to define a threshold with 100% accuracy for detecting arm use. Based on the highest Youden's index, four movement intensity thresholds defining arm use were determined: for both standing and lying/sitting activities, separately for the affected and unaffected arm (Figure 5.3: see horizontal lines). Table 5.2 shows that, after applying those thresholds in the development dataset, the sensitivity, specificity, and agreement between the Activ8-AUM data and the video data were all 74% or higher.

Validation of the Activ8-AUM

Table 5.3 shows the number of epochs, the sensitivity, specificity, and agreement between the Activ8-AUM and the video of the validation dataset for the different groupings of data. Table 5.2 directly compares these variables in the development and validation dataset. The validation dataset contained 2802 5-s epochs for the unaffected arm and 2557 5-s epochs for the affected arm, which corresponds to ≥ 3.5 h of measurement. Overall, detecting arm use had a sensitivity of 73% and a specificity of 77%. In case arm use was not correctly determined it was determined as no arm use. When evaluating the validity per class of Figure 5.1, or per activities of the protocol, the accuracy was consistent but with some important exceptions. 'Arm use without movement' (class 1) was frequently detected incorrectly, especially in the unaffected arm (sensitivity unaffected arm: 24%; affected arm 42%). An example of this is holding onto the table during standing, which is arm use without movement but which was often incorrectly classified as no arm use. Also 'no arm use with movements' (class 4) was less accurately detected (specificity unaffected arm: 53%; affected arm: 64%). As expected, when comparing the validity between the development and validation dataset, the sensitivity, specificity, and agreement was -10 to 11 points lower (Table 5.2, Validation dataset).

Table 5.2 Data on sensitivity, specificity, and agreement in total time between Activ8-AUM and video recording (all in %) in the development dataset and validation dataset.

		Development dataset			**Validation dataset**		
		Sensitivity	**Specificity**	**Agreement**	**Sensitivity**	**Specificity**	**Agreement**
Lying/ Sitting	(A) Unaffected arm	80	74	77	71	80	76
	(B) Affected arm	78	90	89	78	78	78
Standing	(C) Unaffected arm	77	76	77	67	75	69
	(D) Affected arm	77	82	80	87	74	78

Table 5.3 Data on sensitivity, specificity, and agreement in total time between Activ8-AUM and video recording (all in %) in the validation dataset.

			n	Sensitivity	Specificity	Agreement
Overall data			5359	73 (3-100)	77 (37-95)	75 (27-88)
Per arm		Unaffected arm	2802	69	79	73
		Affected arm	2557	82	76	78
Per class	Arm use without movement (class 1)	Unaffected arm	267	24	N/A	24
		Affected arm	154	42	N/A	42
	Arm use with movement (class 2)	Unaffected arm	1360	78	N/A	78
		Affected arm	600	93	N/A	93
	No arm use without movement (class 3)	Unaffected arm	1055	N/A	82	82
		Affected arm	1490	N/A	79	79
	No arm use with movement (class 4)	Unaffected arm	116	N/A	53	53
		Affected arm	298	N/A	64	64
Per activity	Lying without an arm task	Unaffected arm	109	N/A	90	90
		Affected arm	118	N/A	89	89
	Sitting without an arm task	Unaffected arm	495	54	81	77
		Affected arm	455	77	79	79
	Standing without an arm task	Unaffected arm	318	8	85	55
		Affected arm	311	N/A	84	84
	Sitting with an arm task	Unaffected arm	842	69	78	73
		Affected arm	731	77	73	75
	Standing with an arm task	Unaffected arm	311	82	80	82
		Affected arm	278	78	64	69
	Vacuuming	Unaffected arm	119	57	52	56
		Affected arm	117	93	68	77
	Hanging laundry	Unaffected arm	130	98	N/A	94
		Affected arm	126	100	90	94
	Packing a bag	Unaffected arm	62	97	N/A	92
		Affected arm	41	100	44	78
	Kitchen activities	Unaffected arm	263	58	50	57
		Affected arm	228	96	65	79
	Personal care activities	Unaffected arm	113	94	31	87
		Affected arm	112	59	88	76
	Throwing a ball	Unaffected arm	40	100	N/A	70
		Affected arm	40	N/A	54	68

DISCUSSION

In this study, we developed and validated the Activ8-AUM to measure arm use in people after stroke. This device consists of three simple and low-cost accelerometers (one on the unaffected thigh and the others on each wrist). The device provides data on the movement intensity of the arms, and on postures/movements based on the leg sensor. Combining these different types of data allowed to define body posture-specific movement intensity thresholds for arm use, and to separate arm movement during walking from arm movement during sitting and standing. In the validation part of the study, the Activ8-AUM showed similar results in detecting arm use as the previously developed Vitaport ULAM[20], which measured more detailed data on postures/movements and arm use. However, the Vitaport ULAM is not practical for use in daily life.

Arm use in people after stroke has also been measured by other groups. In the present study, the way of measuring arm use was conceptually similar to the approach of Schasfoort et al.[22] and Michielsen et al.[6] using the Vitaport ULAM, and to Rand & Eng[15] using accelerometers on the wrists and hip. Other studies used more simple sensor configurations based on sensors on each wrist[10,11,13,23-25]. Besides measuring arm use in daily life, Lemmens et al.[26] focused on the detection of specific activities of daily life such as ‘drinking from a cup’ and ‘brushing hair’. For this they needed several accelerometers on the hand, wrist, arm and chest. Thus, most of the available devices do not use information on postures/movements or a movement intensity threshold; however, the effect of using this additional information and threshold has not yet been evaluated.

A general limitation of using accelerometry to quantify arm use is that not all arm movement should be considered as arm use and, vice versa, no arm movement is not necessarily an indication of no arm use. The Activ8-AUM has this limitation too: arm use was poorly detected during holding an object or leaning when arms are displaced little or not at all (Table 5.3, class 1). Idem, no arm use was less accurately detected when the arm was moving (class 4). However, adding data on postures/movements was helpful in reducing this latter form of mistakes: arm movement during walking was not incorrectly classified as arm use, due to the known body movement of walking. Although, during no arm use, arm movements due to slight general trunk movement during standing were still misclassified as arm use. This general limitation of accelerometry should not hamper future usage of the Activ8-AUM. Arm use which is difficult to detect with accelerometry (holding, leaning, small manipulations) is mainly preceded and followed by arm movements to bring the arm in the right position. While in people after stroke, less leaning and holding with the affected arm is expected, easily detectable arm movements will also be performed less often. Moreover, it was considered highly likely that arm movement and arm use is related[27]. Therefore, although it is not possible to directly measure arm use with accelerometry, the amount of arm movements were considered a meaningful parameter.

Development of the Activ8-AUM

In the development part of this study, we determined four movement intensity thresholds above which an epoch is optimally classified as arm use. Four different thresholds were used to take into account the differences in movement intensity between lying/sitting and standing, and between the affected and unaffected arm. This approach was supported by the data: the optimal threshold for standing (when more body movement affecting arm movement can be expected) was higher than for lying/sitting. Also, the optimal threshold for the affected arm (associated with slower movements and lower movement intensities) was lower than for the unaffected arm. It should be noted, however, that the severity of a stroke will affect the movement and movement intensity of the affected arm. In the present approach, thresholds are based on group level data, which may be suboptimal for individuals. In the future, more individualized thresholds could be explored, e.g., using different thresholds for different levels of arm function based on standardized tests (e.g., the Frenchay Arm Test[19]). To determine the four optimal movement intensity thresholds, the Youden's index was used because it combines sensitivity and specificity[21]. We felt that, for our device, sensitivity and specificity are equally important and that, therefore, the highest sum of both is the best criterion to define the thresholds. An alternative criterion could have been the highest agreement; however, the benefit derived from the highest sum of both the sensitivity and specificity would then be lost. Moreover, our data showed that agreement was a less discriminative criterion, because several thresholds showed comparable optimal agreement percentages. It is important to realize that the sensitivity and specificity and, therefore, the Youden's index are influenced by the activities included in the protocol, and the ratio of arm use and no arm use. Thus, whether the four determined thresholds will be as optimal to measure arm use in daily life will depend on the extent to which the activities of daily life differ from those in the protocol, and the ratio of arm use and no arm use in daily life. To take this into account, our data were adjusted to create a ratio comparable to that established previously in people after stroke[6].

Validation of the Activ8-AUM

In the present study an overall agreement of 75% was found between the Activ8-AUM data and the video data, which is comparable to the agreement scores of the previously developed Vitaport ULAM[20]. That earlier system provided meaningful outcomes in several studies in people after stroke[6] and in patients with complex regional pain syndrome[22], which supports the conclusion that the agreement percentage of 75% is sufficient for application in descriptive and evaluative studies. However, the large individual difference in overall sensitivity, specificity, and agreement showed that movement intensity thresholds, which are based on group level data, are not optimal for all individuals. One reason for this is the ratio of arm use and no arm use. Although in the total group we adjusted our data to create a ratio comparable to that in daily life of people after stroke[6], the individual data still show a large difference in that ratio, especially in participants with low agreement scores. Inspection of specific activities showed that standing without arm task was often detected incorrectly. During standing, although no arm tasks were imposed, some participants were holding onto a table or a walking aid. In the video analyses this was scored as arm use (without movement, class 1), whereas the Activ8-AUM detected this as no arm use due to the low movement intensity; this is a typical example of the above described source of misdetection.

Limitations

Some limitations of the study need to be addressed. First, we used one Activ8 on the thigh to detect postures/movements, in order to distinguish between lying/sitting, standing, and other body movements. This application of the Activ8 was previously validated to measure postures/movements in healthy persons[2] and people after stroke[3], and showed good discrimination between lying/sitting, standing, and other postures and movements. Nevertheless, detection of postures/movements is not flawless and might have influenced the periods in which arm use was determined. However, we expected this influence to be small, i.e., based on the accuracy of the Activ8, very few periods of actual lying/sitting or standing will be missed. A second limitation is that quantifying the reality (i.e., what actually happened), per second, based on the videos was difficult and prone to subjective interpretation. To decrease this effect, classification of arm use was carefully performed based on well-defined criteria for the different classes. Classification was first practiced and then performed by one researcher; agreement with a second researcher was obtained in case of doubt.

CONCLUSIONS

In this study a novel clinically applicable and easy-to-use arm activity monitor was developed. A good agreement between the Activ8-AUM and the video recordings was reached for measuring arm use when a movement intensity threshold for the arm accelerations was combined with postures/movement data. Besides this good agreement, the Activ8-AUM has an easy-to-use configuration with three simple and low-cost accel-

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[2] Horemans et al. The Activ8 Activity Monitor: validation of posture and movement classification

[3] Fanchamps et al. The Accuracy of the Detection of Body Postures and Movements Using a Physical Activity Monitor in People after a Stroke

erometers placed on the leg and on both wrists. Therefore, the Activ8-AUM is a promising device for researchers and clinicians to measure arm use in people after stroke.

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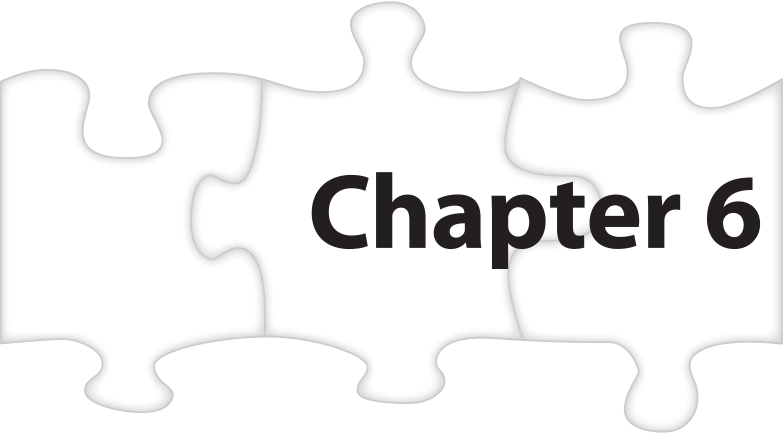

Chapter 6

Recovery of objectively measured arm use in daily life after stroke and its relationship with arm function

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ABSTRACT

Background: A stroke often results in functional impairment and in decreased daily-life use of the affected arm. However, it remains unclear how actual arm use recovers after a stroke and how this relates to arm function.

Objective: To investigate the recovery of objectively measured arm use and its relationship with arm function during stroke rehabilitation.

Methods: In fifteen individuals with initial arm paresis after a stroke and receiving usual care in a rehabilitation center, arm use and function were assessed at 3, 12, and 26 weeks after a stroke. Arm use was repeatedly measured for one consecutive week using an accelerometry-based arm use monitor. The primary outcome was the ratio of movement counts of the affected arm divided by those of the unaffected arm, calculated during sitting and standing, as assessed by the activity monitor. Arm function was measured with the Fugl-Meyer Assessment scale.

Results: On average, the arm use ratio increased from 0.25±0.14 (3 weeks) to 0.42±0.25 (12 weeks; 3-12 weeks p=0.002) and to 0.51±0.24 (26 weeks; 12-26 weeks p=0.009), but still remained low and with large inter-individual variability. The arm use ratio was positively related to arm function and this was more clearly observed at higher levels of arm function.

Conclusions: This study shows that daily-life arm use remains asymmetrical up to six months after a stroke. Since this arm use is essential in daily-life activities and to prevent non-use, interventions are needed to stimulate use of the affected arm in individuals with an asymmetrical pattern of arm use after a stroke.

INTRODUCTION

After stroke, individuals often suffer from impairment of the affected arm; initially, 75% suffers from impaired arm function, improving to 65% after 6 months[1,2]. Besides this impairment, individuals experience decreased actual use of their affected arm in daily life, leading to limitations in daily-life activities, greater dependency, and restrictions in social participation[3,4]. Practicing arm movements with the affected arm is a key element during motor rehabilitation after a stroke. However, from the patient's perspective, it is not so much the ability to move the affected arm (hereafter called 'arm function') that is the ultimate goal of stroke rehabilitation, but to restore actual arm use in daily life (hereafter called 'arm use')[5,6].

Currently, it is unclear how actual arm use during daily life recovers after a stroke and how this relates to arm function. Cross-sectional data of previous studies have shown that objectively measured (accelerometry) arm use, is correlated with several measures of arm function, e.g. the active range of motion of the shoulder, elbow and wrist, the Fugl-Meyer Assessment (FMA), and the Action Research Arm Test (ARAT)[7-11]. However, being able to move the affected arm and having the potential to use this arm does not necessarily lead to actual arm use in daily life[12-14], which may lead to so-called 'non-use' of the affected arm[4,15]. Therefore, it is important to assess not only arm function with clinical measures (such as the FMA or the ARAT), but to also objectively measure actual arm use during stroke rehabilitation[16]. Using data on arm use and on arm function allows to quantify the 'gap' (the so-called non-use of the affected arm) between these two parameters. New insight in patterns of non-use provide opportunities for more appropriate therapeutic options and may help improve stroke rehabilitation.

Several methods are available to measure arm use; of these, accelerometry is generally considered the most suitable because it is objective, easy to use, widely available and has previously been applied[4,10,16,17]. However, measuring arm use during stroke rehabilitation is much less common than measuring, for example, general physical activity[18]. This might be due to practical issues, such as the commercial availability of sensors measuring general physical activity as compared to sensors measuring arm use. However, objectively measuring arm use is also hampered by the complexity of the interpretation of the measured arm movements to describe arm use. For interpreting arm movements, it is necessary to distinguish between arm movements caused by walking or other whole-body movements and arm movements occurring during other body postures (e.g. sitting and standing) since, in these latter postures, arm movements are more likely to be arm use and not the result of body movement (such as arm sway during gait). To enable this, our group developed and validated an easy-to-use arm use monitor to objectively measure arm use with accelerometry[19]. This device measures accelerations of both arms simultaneously and combines these data with body postures and movements (hereafter called ‘postures/movements’) to obtain a more accurate estimation of arm use. Moreover, this monitor is easy-to-use, non-invasive to wear and relatively inexpensive, making it a clinically applicable monitor.

In this longitudinal study, the new monitor was used to repeatedly measure arm use to examine the recovery of arm use during the first 26 weeks after a stroke. Also investigated was the relationship between arm use and arm function during the first 26 weeks after a stroke.

METHODS

Participants

The present study was part of a larger longitudinal cohort study (PROFITS) aimed to improve prognostic models for motor recovery poststroke. All individuals entering Rijndam Rehabilitation (Rotterdam, the Netherlands) between September 2016 and April 2017 after an ischemic or hemorrhagic stroke were screened by a research assistant. Inclusion criteria were a paretic arm or leg at admission to the rehabilitation center (defined as NIHSS 5A/B or 6A/B 4 ≥ score > 0), aged ≥18 years, a Mini–Mental State Examination of at least 20, and the ability to sit at least 30 min with back support. Excluded from the study were individuals who were ≥ 3 weeks after the stroke. The study was approved by the Medical Ethics Committee of Erasmus Medical Center Rotterdam, the Netherlands (MEC-2015-687) and all participants gave written informed consent.

Procedure

At the start of the study, all participants were inpatients at Rijndam Rehabilitation where they received ‘usual care’ stroke rehabilitation. Here, the ‘usual care’ for arm rehabilitation is based on the principles of the Concise Arm and Hand Rehabilitation Approach in Stroke (CARAS)[20]. As the present study was purely observational, this ‘usual care’ was not adapted, neither the amount nor the content of the rehabilitation. Arm use as well as clinically-assessed arm function was measured at fixed time points after the stroke i.e. at 3 weeks (T1), 12 weeks (T2), and 26 weeks (T3). At T1, the following information was collected on participants and their stroke characteristics. The type, location, and side of the stroke were extracted from the medical records, as was the score on the Montreal Cognitive Assessment[21], assessed by a physician on admission to Rijndam Rehabilitation. The left-right handedness before stroke was determined by asking the participants. Due to the individual goal setting in ‘usual care’, some participants were still at the rehabilitation center at T2, whereas at T3 all participants were at home and were visited by a research assistant for the follow-up measurements.

Instruments: arm use

Arm use was measured by the Activ8 arm use monitor (Activ8-AUM); participants were asked to wear the monitor for one consecutive week. The Activ8-AUM consists of three Activ8 Physical Activity Monitors (Remedy Distribution Ltd, Valkenswaard, the Netherlands). One of these single-sensor, triaxial accelerometers was attached to the unaffected thigh and the two others to each wrist. This configuration was developed and validated in a previous study[19]. In short, movement counts of the arms (expressing the amount and intensity of movement) are determined based on the acceleration data measured with the sensors on the wrists, while postures/movements are determined based on the leg sensor. The posture/movement detection of the Activ8 in people after stroke was previously validated as well[22]. After the measurement, all data were combined to quantify arm use (described below in Data analysis Activ8-AUM). The sensors on the wrists were attached to the dorsal side with watch-type wristbands and were taken off during the night and during activities involving water, e.g. showering, bathing, and swimming. The leg sensor was attached on the ventral side of the thigh between hip and knee with water resistant, anti-allergic skin tape, and was worn continuously for seven days.

Instruments: arm function

Arm function was measured by the Fugl-Meyer Assessment of the arm (FMA-UE). The FMA-UE consists of nine components examining voluntary movements and the ability to perform arm movements outside of patterns of abnormal joint coupling (flexion synergies)[23,24] outside of synergies. Scores on the FMA-UE range from 0-66, with higher scores indicating better motor function of the affected arm[23,25]. The FMA-UE is often considered a measure of behavioral restitution reflecting the amount of neurobiological recovery of motor function[26].

Data analysis

After each measurement, data from all three Activ8s were downloaded to a PC and were the input for an in-house MATLAB (MathWorks, Natick, MA, USA) program determining arm use. The first step was to synchronize the Activ8s based on the time stamps within the data files. Then, the measurement period was selected. Only waking hours were analyzed, for which we chose 7 am to 10 pm. Within this period, nonwear of the arms was detected when at least one of the two wrist sensors measured zero movement counts for at least one hour. Data were used for analysis when at least three valid days of data were available, defined as at least ten hours of data without nonwear. Then, epochs were selected during which participants were in a sitting or standing position as assessed by the leg sensor. Of these selected data, outcomes were calculated per valid day and then averaged to a mean value per measurement. The primary outcome measure of the present study was arm use defined as the ratio of the movement counts of both arms, calculated as the sum of the movement counts of the affected arm during sitting and standing divided by the sum of the movement counts of the unaffected arm during sitting and standing. The secondary outcome measure, the total movement counts during sitting and standing, was calculated for each arm separately to be able to attribute changed arm use ratio to a change in use of the affected arm, or of the unaffected arm, or a combination of both.

Statistical analysis

In this longitudinal study, most data were presented in a descriptive way on individual level. Generalized estimating equation was used to determine the effect of time on the arm use ratio and the movement counts of each arm, and to calculate the mean arm use ratio for each time point. The measurement occasion (as the factor time) was added to the model as the only independent variable. To assess whether the arm use ratio deviated from the value for healthy persons (reported in literature to be 0.95[27]),

Table 6.1 Characteristics of the participants and information related to their stroke.

Participant ID number	Gender	Age at stroke (years)	Type of stroke	Supra or infra tentorial stroke	Side of stroke	Dexterity before stroke	MOCA score at start of inpatient rehabilitation	End of inpatient rehabilitation (weeks after the stroke)
1	Male	37	Infarct	Supra	Right	Right	27	8
2	Male	66	Venous hemorrhage infarct	Supra	Left	Right	11	6
3	Male	62	Infarct	Supra	Right	Left	27	3
4	Female	38	Infarct	Supra	Right	Right	21	13*
5	Male	61	Infarct	Supra	Right	Right	23	11
6	Male	54	Infarct	Infra	Left	Right	22	14*
7	Female	57	Infarct	Supra	Left	Right	25	12*
8	Male	47	Infarct	Supra	Right	Right	20	10
9	Female	62	Infarct	Supra	Left	Right	27	10
10	Male	58	Infarct	Supra	Right	Right	23	23*
11	Male	65	Infarct	Supra	Right	Right	22	4
12	Male	60	Infarct	Supra	Left	Left		17*
13	Male	48	Infarct	Supra	Right	Right	29	6
14	Male	39	Infarct	Supra	Left	Right	9	11
15	Female	59	Infarct	Supra	Left	Right	25	10

**These participants were measured at the rehabilitation center at T2 (12 weeks after the stroke). MOCA = Montreal Cognitive Assessment.*

a one-sample t-test was performed with 0.95 as test value. All statistical analyses were performed with SPSS for Windows version 24 (SPSS Inc., Chicago, IL, USA) and a p-value ≤ 0.05 was considered statistically significant.

RESULTS

Participants

Included were 15 individuals after a stroke (11 males; mean age 54.6±9.9 years, FMA-UE 23±21 at T1) (Table 6.1). At T1, Activ8-AUM data were missing for three participants: for two because of device failures while the other participant had insufficient valid days (≤ 3 days) both at T1 and T2. At T3, data on arm use were missing for two other participants: for one because of insufficient valid days while the other participant was lost to follow-up. Scores for the FMA-UE were missing for three participants (each at one time point).

Change in arm use

Figure 6.1 shows the course of the arm use ratio during the first 26 weeks after the stroke. At T1, the mean arm use ratio was 0.25±0.14 and showed a significant increase at T2 to 0.42±0.25 (T1-T2 p=0.002) and at T3 to 0.51±0.24 (T2-T3 p=0.009). Figure 6.2 shows the course of the movement counts of the affected and unaffected arm after the

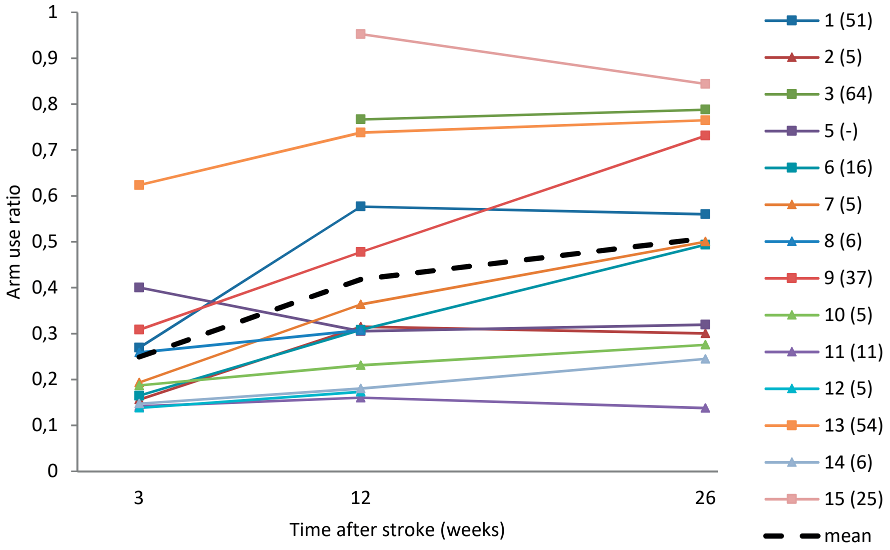

Figure 6.1 Change in arm use ratio in the 26-week period after the stroke. The ID numbers of the 15 participants (right panel) correspond to those in Table 6.1. The numbers between brackets are the scores on the Fugl-Meyer Assessment of the affected arm at 3 weeks after the stroke. Of all participants, the half with the lowest FMA scores are indicated by ▲ and the remainder by n.

stroke. The movement counts of the affected arm were on average lower than those of the unaffected arm; at baseline this was about a four-fold difference while, over time, the

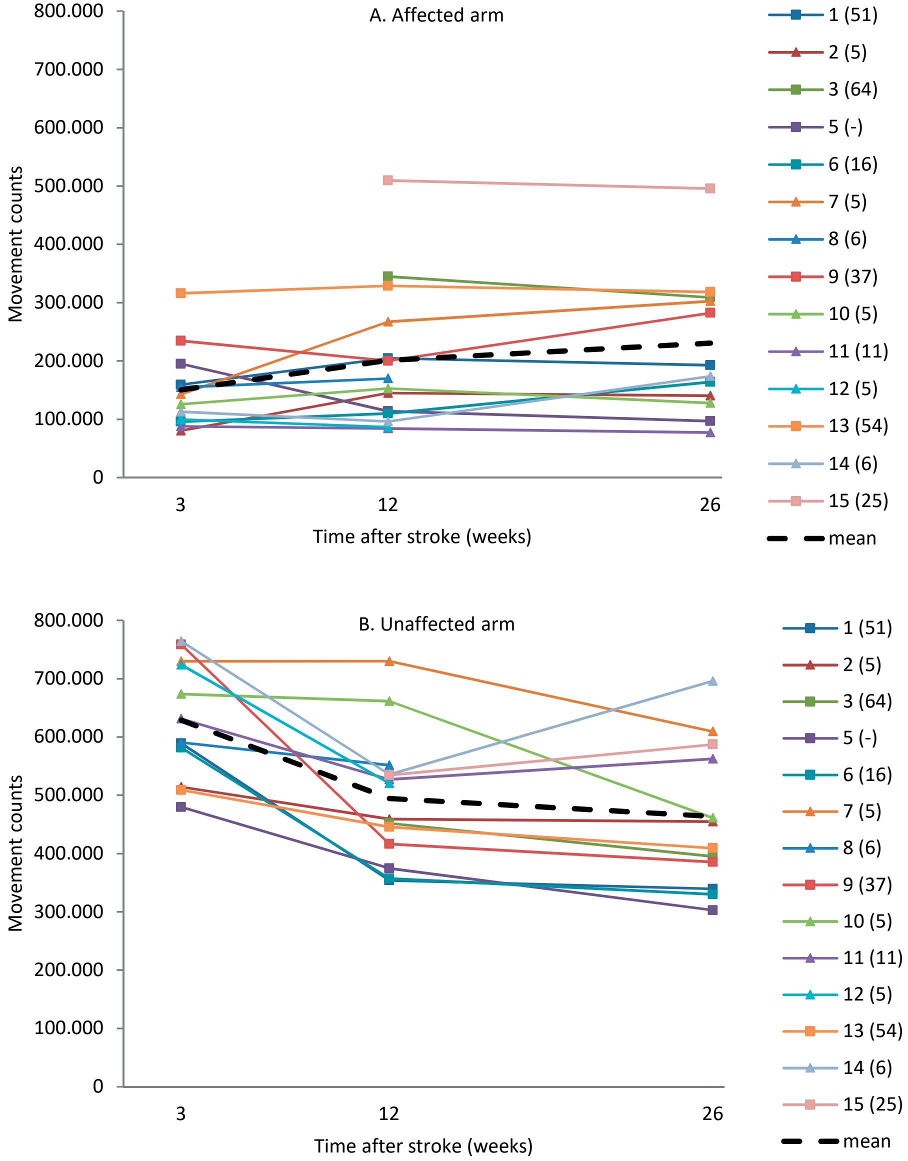

Figure 6.2 Change in movement counts of (A) the affected arm, and (B) the unaffected arm in the 26-week period after the stroke. The ID numbers of the 15 participants (right panel) correspond to those in Table 6.1. The numbers between brackets are the scores on the Fugl-Meyer Assessment of the affected arm at 3 weeks after the stroke. Of all participants, the half with the lowest FMA scores are indicated by ▲ and the remainder by n.

difference decreased to a two-fold difference. The increase of movement counts of the affected arm and the decrease of movement counts of the unaffected arm were significant over time (affected arm T1-T3 $p<0.01$; unaffected arm T1-T3 $p<0.01$). The amount of time that participants were sitting and standing, during which arm use was analyzed, showed a significant decrease over time (T1-T3 $p<0.01$). On average, at T1 participants sat 785 min per measurement day compared with 712 min per measurement day at T3. Even when taking this decrease in sitting/standing into account, the decrease in movement counts of the unaffected arm was still significant (T1-T3 $p<0.01$). Figure 6.2 also shows that the increased arm use ratio was a combined effect of increased use of the affected arm and decreased use of the unaffected arm. Both figures show large variability between participants, in both level of arm use and in change over time. Although the arm use ratio increased, it remained significantly lower than the average ratio of 0.95 reported for healthy persons[27] ($p<0.001$ for T1, T2 and T3).

Relationship between arm use and arm function

Figure 6.3 shows the relationship between the arm use ratio and arm function; participants with a better arm function had a larger arm use ratio. However, this is clearer above a FMA-UE of 40.

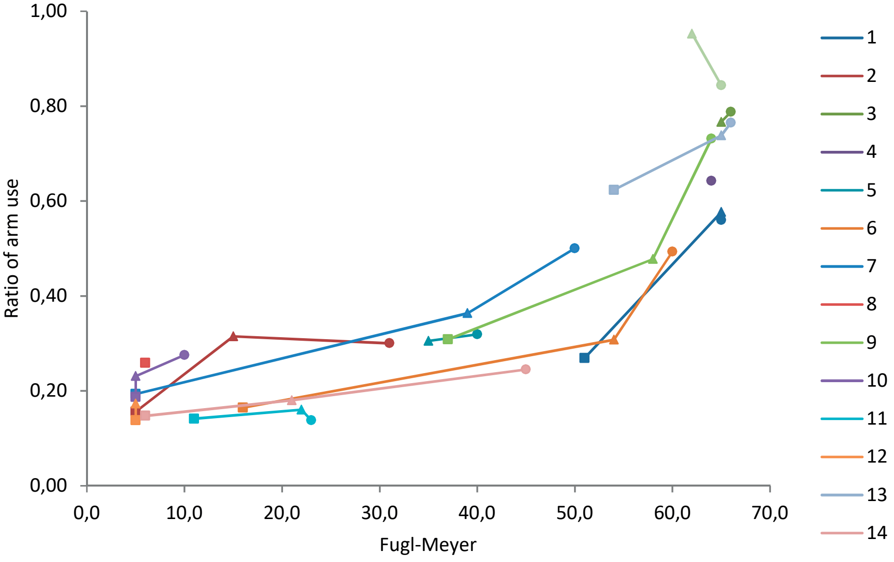

Figure 6.3 Relationship between scores on the Fugl-Meyer Assessment of the affected arm and the arm use ratio. The ID numbers of the 15 participants (right panel) correspond to those in Table 6.1. Symbols: n scores at 3 weeks after the stroke, ▲ scores at 12 weeks after the stroke, and l scores at 26 weeks after the stroke.

DISCUSSION

This longitudinal study with repeated measurements at fixed time points after the stroke, examined the recovery of arm use in daily life and its relationship with arm function during stroke rehabilitation. During the first 26 weeks after the stroke, although the arm use ratio increased caused by an increased use of the affected arm and by a decreased use of the unaffected arm, the unaffected arm was still highly dominant (mean ratios ranging from 0.25 to 0.51). Despite large variability in arm use ratio and recovery pattern, at 26 weeks after the stroke the mean arm use ratio was still lower than that reported for healthy persons[27]. The arm use ratio was positively related to arm function and this was more clearly observed at higher levels of arm function (FMA-UE score >40).

The results of the present study show that the mean arm use ratio was strongly decreased at 3 weeks after the stroke but improved over time, indicating increased symmetrical arm use. However, although the mean arm use ratio increased from 0.25 (T1) to 0.51 (T3), this is still considerably less than the almost symmetrical 0.95 reported for healthy persons[27]. Comparable results on symmetry of arm use after a stroke were found in previous cross-sectional studies: participants (in both the sub-acute and chronic phase) used their affected arm two to four times less than their unaffected arm[4,8,9,12,13]. The only available longitudinal study reported arm use ratios of around 0.6, with large inter-individual variability[14]. The increased mean arm use ratio of the present study indicates a recovery towards a more symmetrical pattern of arm use, resulting from both an increased use of the affected arm and a decreased use of the unaffected arm (Figure 6.2). This indicates that, early after a stroke, individuals compensate for the decreased use of their affected arm by increased use of their affected arm and that this compensatory behavior starts to decrease in the first months after stroke. However, in the present study, the type of rehabilitation that participants received may have played a role in their changed behavior, i.e. during rehabilitation, our participants were stimulated to re-use their affected arm to perform daily-life activities and to use both arms to perform bimanual activities.

In this study, recovery of the arm use ratio in the first 26 weeks after the stroke was highly variable. Although the arm use ratio was considerably affected at 3 weeks after the stroke, some participants had more symmetrical arm use than others, and the significant increase of the arm use ratio over time did not occur in all participants. In some, the ratio increased over the entire 26-week period, whereas in others it increased only in the first 12 weeks after the stroke, or there was no increase at all. Reasons for this variability might include: i) individual stroke characteristics (e.g. initial arm function, dominant arm affected or not, cognitive impairments, etc.) or ii) personal and/or psychological issues (e.g. motivation and self-efficacy)[28-30]. Although we did not assess these types of characteristics, we recommend to include them in future research.

The present results also demonstrate a relationship between arm use and arm function; however, both the overall data and individual data show that this is a nonlinear relationship. This indicates the need for a threshold in arm function before the affected arm is functionally used in daily life and thereby the arm use ratio starts to increase during rehabilitation, irrespective of normalization of arm use ratio. This nonlinear relationship between arm use and arm function was found in earlier cross-sectional studies[11]. Although other studies assessing arm use and arm function also found some relationship they: i) only calculated Spearman's correlation coefficients and did not examine the nature of the relationship, and ii) although accelerometry was used to measure arm use, this was for a maximum of 24 h only[8,9].

Strengths of the present study were its longitudinal design with repeated measurements at fixed time points up to 26 weeks after the stroke encompassing objectively measured arm use in daily life using a validated and standardized accelerometry based paradigm with a one week consecutive observational period. There are also some limitations. First, the sample size is small and some data are missing. Second, received therapy at the rehabilitation center was not standardized, nor recorded, but rather reflected 'usual' care. Therefore, the influence of therapy on arm use cannot be determined. Future studies should take into account the amount, duration, frequency and type (unimanual/ bimanual) of therapy that each participant receives.

From a clinical perspective, there is added value for measuring actual arm use in daily life next to assessing arm function and capacity by e.g. FMA-UE or ARAT. The present study shows that there are individuals with a gap between arm use in daily life and arm function within the first 26 weeks after the stroke, indicating being at risk to develop non-use of the affected arm. It is important to target those individuals at risk and develop specific strategies to prevent non-use of the affected arm. We hypothesize that stimulating arm use without having sufficient arm function could be demotivating, while stimulating arm use too late could trigger the development of non-use. Since arm use in daily life and the recovery of arm use after a stroke were found to be highly variable, rehabilitation programs targeting arm use should be preferably be patient-specific to stimulate arm use at the appropriate moment in the aim to optimize stroke rehabilitation.

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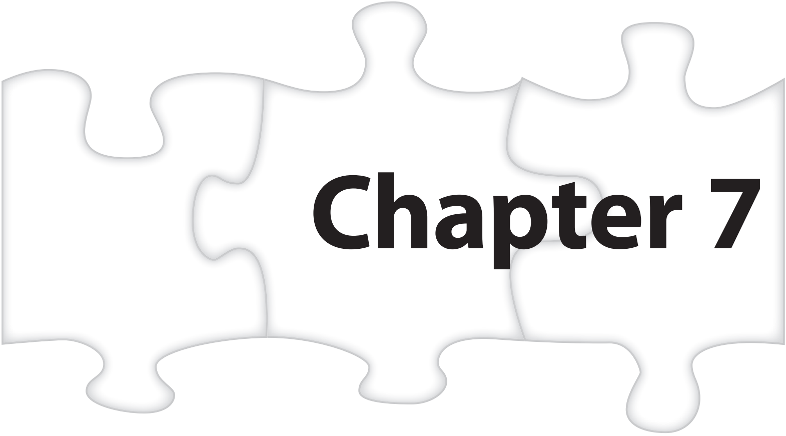

Chapter 7

General discussion

The primary aim of this thesis was to investigate two methodological aspects of measuring physical behavior from the perspective of stroke rehabilitation. The methodological aspects were: i) the effect of applying different operationalizations of the construct to be measured, and ii) the validity of a measurement device. These aspects were investigated with respect to three components of physical behavior: sedentary behavior, body postures & movements, and arm use. Another aim was to apply physical behavior monitoring to describe daily-life arm use in people after stroke.

More specifically, the effect of different operationalizations of sedentary behavior was assessed on sedentary behavior outcomes in healthy people (***Chapter 2***) and in people after stroke (***Chapter 3***). The validity of two different monitors was assessed: an activity monitor to measure body postures & movements in daily life (***Chapter 4***) and a custom-made activity monitor to measure arm use in daily life (***Chapter 5***). Finally, the latter activity monitor was used to measure the recovery of arm use during the first six months after a stroke, and this was related to the recovery of arm function during the same period (***Chapter 6***). This chapter discusses the main findings in the context of the existing literature, as well as clinical implications, and it offers some recommendations for future research.

MAIN FINDINGS

The main findings of this thesis are summarized in Figure 7.1. It was found that different operationalizations of sedentary behavior had a clear effect on the outcomes related to the total amount of sedentary time and the way sedentary time accumulates in bouts, in healthy people and in people after stroke. In both groups, the differences were not only significant but also large enough to acknowledge differences between the different operationalizations. Next, we found that the Activ8 Physical Activity Monitor [1] (the Activ8) was sufficiently valid to detect body postures & movements in people after stroke. The Activ8 arm use monitor (the Activ8-AUM) was developed and proved to be sufficiently valid to measure arm use during lying/sitting and standing in people after stroke. Therefore, both these activity monitors can be used to measure components of physical behavior in stroke rehabilitation. The results of using the Activ8-AUM in people after stroke showed that, 3 weeks after the stroke, the arm use ratio was low, i.e. the arms were used in a non-symmetrical way and with low use of the affected arm. During the first 26 weeks after the stroke, although the arm use ratio increased it remained significantly lower than the ratio in healthy people, as reported by others[2]. Moreover, both the arm use ratio and its increase showed considerable variability between participants. The arm use ratio seemed to be non-linearly related with arm function, because the positive relation between arm use and arm function was more clearly observed at higher levels of arm function.

This general discussion is approached from two perspectives as described in Figure 7.1, i.e. from the top of the figure that presents the methodological aspects and the application of measuring physical behavior, and from the bottom of the figure that presents the components of physical behavior.

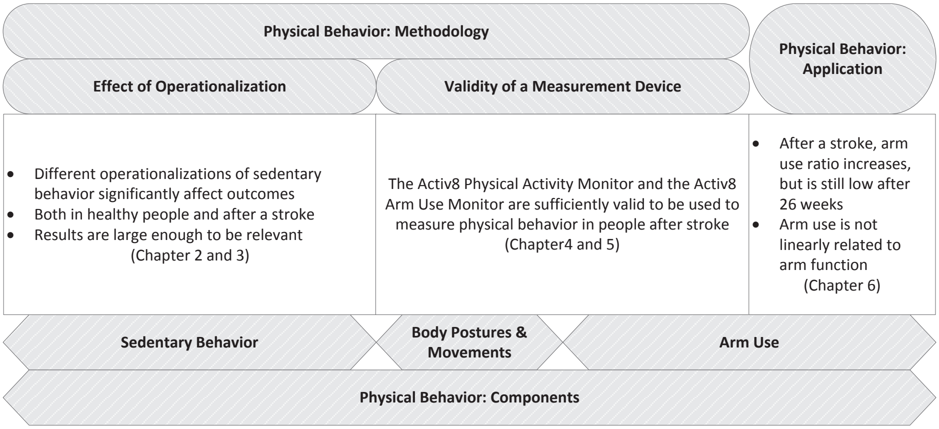

Figure 7.1 Overview of the main findings of this thesis.

PHYSICAL BEHAVIOR: METHODOLOGY

Effect of operationalization

Different operationalizations of sedentary behavior lead to important differences in outcomes, as shown in ***Chapter 2*** and ***3***. During the process of operationalization, the construct to be measured is translated into a measurable variable. However, several options are available regarding how to operationalize a construct. For example, sedentary behavior has been operationalized as 'the amount of time someone sits' [3, 4] or as 'the amount of time with low energy expenditure' [5, 6], whereas the consensus definition combines both of these [7]. Since the effect of applying different operationalizations has not previously been investigated, our use of different operationalizations showed relevant differences in sedentary time and the way in which this time was accumulated.

In this thesis, we studied the effect of operationalization in sedentary behavior; however, this effect is not solely an issue of this specific component of physical behavior. The translation from a theoretical construct to a measurable variable also plays a role in other components. Physical activity is a broad concept of complex behavior that can be operationalized using different dimensions: frequency, intensity, time and type (FITT) [8, 9]. Arm use is a theoretical construct as well that can be operationalized in different ways. For example, it can be operationalized as the number of specific functional activities like drinking and hair brushing [10], or the quality of specific movements like reaching and grasping [11, 12]. In this thesis, we operationalized arm use as '*active movement of parts of the arm, holding objects or leaning during sitting and standing*'.

Besides operationalization, other decisions in measuring physical behavior may also influence the outcome, e.g. the way of calculating the outcome measure. In ***Chapter 6*** we calculated the ratio of arm use as *'the movement counts of the affected arm divided by the movement counts of the unaffected arm'*. We chose this particular formula in order to be in line with other studies on this topic [13, 14]. However, we could also have calculated the ratio as '*the movement counts of the affected arm divided by the movement counts of both arms together'*. In that case, the same arm use would have resulted in a different value of the ratio, which hinders comparison of our results with other studies. Another example of a difference in calculation is the relative duration of physical activity (expressed in %) during one day. In this case it is important to establish what '100%' actually represents; for example, does it literally mean during 24 h, or does it refer to the wear-time of the monitor.

Back in 2012, Taraldsen et al.[15] reported the urgent need to develop consensus on activity protocols and outcome measures. The studies in ***Chapter 2*** and ***3*** confirm this need. The use of similar activity protocols and operationalizations, and calculating outcomes measures in the same way, allows to compare and exchange data across studies. Large meta-analyses can then be performed to investigate health effects and working mechanisms of physical behavior, without the possible confounding effects of methodological aspects. However, it will probably be impossible to reach consensus (100% agreement) on all of these issues. For example, measuring physical behavior in patient populations sometimes requires population-specific choices of those aspects. Therefore, it is important that authors explicitly describe such choices (e.g. in the Methods section of their study). For future research we recommend to measure physical behavior in accordance with other research groups whenever possible, with at least consensus on the definitions of the terms used. Comparison of data should be done with care and only when studies are sufficiently similar in operationalization, way of calculation, and other aspects that influence outcomes.

Validity of a measurement device

In this thesis two devices were validated: in ***Chapter 4*** a commercially available activity monitor to measure body postures & movements (Activ8 Physical Activity Monitor [1]: the Activ8), and in ***Chapter 5*** a custom-made arm use monitor based on Activ8 sensors (Activ8 arm use monitor: the Activ8-AUM). Both devices were considered sufficiently accurate and suitable (small dimensions, user-friendly, and with low costs) to be used in stroke rehabilitation. Despite technological developments and the increasing number of devices, not all commercially available activity monitors can be used in clinical practice. Many of these devices (e.g. the Fitbit, Apple Watch, Garmin watches, etc.) were primarily developed for general use in large groups of healthy people, and less often for a patient population. Firstly, most activity monitors were developed to measure the intensity of physical activity, which is only one of the components of physical behavior. Very often, body postures & movements and arm use, which are important components in stroke rehabilitation, cannot be measured. Secondly, the reported output of the activity monitors is generally limited to certain basic outcome measures (e.g., total time sitting), whereas caregivers in stroke rehabilitation are also interested in other measures (e.g. number of sit-to-stand transfers interrupting sitting behavior). Finally, most commercially available activity monitors have not been validated (or only to a limited extent) for use in patient populations; moreover, the results cannot be generalized because of deviations in movement patterns.

The validity of an activity monitor is an important issue when the device is to be used in stroke rehabilitation. To draw correct conclusions about the level of physical behavior, the devices should measure accurately and precisely. However, to be used in stroke rehabilitation, other features need to be considered as well, such as the ease of use for the caregiver, the level of wearing comfort, and the costs. However, although all these requirements are important, the validity and reliability of a device is the most crucial item because of the consequences of conclusions and decisions based on the acquired data.

Although the validity of a device is an important issue, concerns have been raised about validation studies of activity monitors [16]. These concerns are related to the standardization of research (discussed above). In addition, and specifically for validation studies, the lack of harmonization of validation protocols is an important issue. Often, the activity protocols of validation studies are not standardized and are restricted to a limited number of activities performed in a laboratory or in a semi-natural setting. In contrast, activity protocols that include i) a standardized part and ii) a semi-structured part in the home setting, increase both comparability with other studies and ecological validity [16]. Based on experience with our validation study, we also recommend to take into account the *applicability* of the activity protocol in different settings. For example, the protocol to be applied in a home setting needs to be performed in many different types of accommodations. When using similar protocols, the effect of the protocol on the validation outcomes will be minimized, since including easily detectable activities improves the validation results, whereas daily-life activities are more difficult to detect correctly. Standardization needs to be done within certain populations, to make it easier to compare the results of different studies and to start a discussion on the interpretation of validation results: e.g. what is 'good', and when should a device be considered valid. Whenever possible, standardization between certain populations is also good, although most of the time validation studies need to be population-specific which may involve different choices about the activity protocol.

PHYSICAL BEHAVIOR: APPLICATION

In ***Chapter 6***, a custom-made arm use monitor was applied to investigate the recovery of arm use in the first months after a stroke. This was a pilot study within the PROFITS study to assess whether adding measurements of arm use are useful in stroke rehabilitation. The PROFITS study aims to develop a clinical infrastructure to obtain an individualized prognosis of functional recovery after a stroke [17]. In this cohort study, functional outcomes are uniformly evaluated within the full care chain of stroke rehabilitation. The results of the study in ***Chapter 6*** show that arm use and arm function are related, although not one-to-one, indicating that arm use in daily life is a unique construct of physical behavior. Therefore, measurements of arm use are potentially valuable in stroke rehabilitation and may be used to improve the individualized prognosis of functional recovery after a stroke.

Activity monitoring is increasingly applied in medical research. Studies using activity monitors generally aim to assess the health effects of physical behavior; this contributes to the important aim of understanding, preventing and treating diseases. In most of these studies, physical activity has been investigated in large cohort studies in the general population, for example the Rotterdam study [18] and the NHANES cohort [19]. However, it is important to apply ambulatory measurements of other components of physical behavior as well. These components provide insight into other aspects of physical behavior, which might have a different relationship with health and disease. The PROFITS study is an example of applying ambulatory measurements to extend our knowledge on the functional recovery of arm use after a stroke. In this thesis, to facilitate measuring body postures & movements and arm use in people after stroke, two activity monitors were validated. These two monitors proved to be sufficiently valid to be used in stroke research and, therefore, should be applied to extend our knowledge on body postures & movements and arm use in people after stroke.

In addition to application in scientific research, the two activity monitors can also be used in the clinical practice of stroke rehabilitation. Currently, it is becoming increasingly important to measure several outcome measures in order to optimize rehabilitation care. The large differences found between participants, described in ***Chapter 6***, highlight the importance of personalized care. However, measuring physical behavior is not yet a routine assessment in stroke rehabilitation. Recently, the American Heart Association concluded that, although physical activity is increasingly stimulated, it is not yet routinely assessed in clinical practice, in contrast to other cardiovascular risk factors [20]. Therefore, they published a statement [20] including concrete recommendations to stimulate routine assessment of physical activity in healthcare settings. In stroke rehabilitation, routine assessment of other components is also important. The monitoring of body postures & movements and arm use can help to personalize rehabilitation care based on actual functional status and individual progress, like the PROFITS study aims to.

To apply physical behavior monitoring in clinical practice, more work is required. As mentioned, there needs to be a consensus on definitions and methodological aspects (operationalization, outcome measures, etc.). Another previously mentioned condition is the use of valid measurement devices. This validity becomes more important when data are used for medical decision-making that has direct consequences for patients, and even more so when this is on an individual level rather than group level. Moreover, there are practical issues to be considered, including the training of caregivers and an infrastructure to safely store data within medical records. Despite this work, there is no reason to postpone implementing routine assessment of physical behavior in clinical practice. Although new insights into the health impact of physical behavior will continue to update and optimize measuring physical behavior in clinical practice, there is enough evidence and knowledge available to start implementing routine assessment of physical behavior in clinical practice right now.

PHYSICAL BEHAVIOR: COMPONENTS

Sedentary behavior

The results of the studies in ***Chapter 2*** and ***3*** show that sitting/reclining/lying and having a low energy expenditure are two different things. It is possible to sit and spend relatively high amounts of energy, for example during sitting on an active sitting product or when playing a game [21, 22]. On the other hand, it is possible to have a low energy expenditure while standing [22, 23]. Recently, the Sedentary Behavior Research Network finished its Terminology Consensus Project and defined sedentary behavior as: *'any waking behavior characterized by an energy expenditure ≤1.5 metabolic equivalents (METs) while in a sitting, reclining, or lying posture'* [7]. According to this consensus definition, sedentary behavior requires both components at the same time: a certain body posture *and* a low energy expenditure. The rationale behind the combination of these two components is that low energy expenditure has negative health effects [24] as does muscle inactivity of the large muscle groups [25, 26]. The 'lying posture' part of this definition was recently added and shows that even the definition of sedentary behavior is still developing and changing.

The health effects of sedentary behavior have been studied over many years although, in the beginning, sedentary behavior itself was not measured. In older studies, sedentary behavior was operationalized as the absence or a low amount of moderate-vigorous physical activity [27]. Sedentary behavior was associated with all-cause mortality [28], perceived poor health [29], and obesity [30]. Strictly speaking, these associations are not correct. Sedentary behavior originates from the Latin word *sedere* which means 'to sit', which is not the same as the absence of moderate-vigorous physical activity. During one day, a person can perform sufficient moderate-vigorous physical activity according to the physical activity guidelines and sit the rest of the day. A second person can fail to meet the recommended levels of physical activity, while he/she barely sits; this is nicely illustrated by the accelerometer data of two random people analyzed by Pate et al. [27].

Nowadays, it is possible to measure both components of sedentary behavior using accelerometry. This enables researchers to separate sedentary behavior from light physical activity and to assess the health effects of both separately. The results of such studies show that sedentary behavior seems to have harmful effects on health, irrespective of the level of physical activity [31, 32]. Therefore, sedentary behavior has become a new target for interventions, as its harmful health effects cannot be canceled out by simply meeting the recommended levels of physical activity [33]. Although sedentary behavior is measured instead of physical inactivity, most studies operationalize sedentary behavior as the amount of time sitting [3, 4] or the amount of time with low energy expenditure [5, 6], thus only one component is assessed. However, a more complete understanding of the physiological working mechanism of both components *and* their possible interaction is needed [34]. Therefore, for future research we recommend using activity monitors that assess both components of sedentary behavior. Based on the results of such studies, the two-component definition can be assessed on its validity and be adjusted if necessary. Ideally, a longitudinal cohort study is designed in which both components of sedentary behavior are measured at several time points. Then, the separated *and* combined effect of postures and different levels of energy expenditure can be related to health outcomes, e.g. biomarkers for cardiovascular disease and lipid profiles, as well as mortality rate.

Body postures & movements

In ***Chapter 4***, the Activ8[1] was validated to measure body postures & movements in people after stroke. Although often used interchangeably, 'physical activity' and 'body postures & movements' are different components of physical behavior. Physical activity has been defined as '*any bodily movement produced by skeletal muscles that results in energy expenditure*' [35], whereas body postures & movements stand apart from energy expenditure and concern the orientation of the body relative to gravity. The aim of measuring physical behavior determines whether physical activity or body postures &

movements needs to be quantified. In health-related issues, energy expenditure is more relevant: a healthy lifestyle includes sufficient moderate-to-vigorous physical activity [36, 37]. On the other hand, body postures & movements are mostly measured to assess motor recovery and muscle function, or to monitor falls. Therefore, it is also important to have valid devices to measure body postures & movements, besides devices that measure energy expenditure.

In the general population and in rehabilitation populations there are reasons to measure body postures & movements, instead of energy expenditure, when assessing physical behavior. For healthy aging, use of the musculoskeletal system to maintain muscle function is a highly relevant aspect [38]. To assess that use, body postures & movements need to be measured, instead of energy expenditure or physical activity. In stroke rehabilitation, motor recovery is an important goal that strives to mobilize people to change from mainly lying and sitting, to standing and walking [39]. From the perspective of energy expenditure, sitting and standing still are relatively similar [22, 23], whereas these activities differ physiologically [24]. Upright activities, including standing, activate large muscle groups and will prevent deconditioning of the locomotion system [24]. Thus, especially in people after stroke, measuring body postures & movements in addition to energy expenditure is relevant to assess functional status and motor recovery.

Data on body postures & movements can also be used to improve other measurements, e.g. to optimize estimates of energy expenditure [40]. Moreover, these data can improve measurements of arm use. Arm movements due to walking are often described as a confounder of measuring arm use [14, 41-43]. Information on body postures & movements can be used to separate arm movements caused by walking and whole-body movements, from arm movements related to actual arm use. Also, when measuring sedentary behavior, it is important to be able to validly measure body postures & movements, as body posture is one of the requirements of sedentary behavior.

Arm use

Arm use is a relevant component of physical behavior in people after stroke, because they might have disturbed motor function of the arm. Therefore, in ***Chapter 6*** we performed a pilot study to assess the recovery of arm use and its relation with arm function. In this thesis, arm use was defined as '*active movement of parts of the arm, holding objects or leaning during sitting and standing*'. Thus, arm use implies conscious and intended movements of a person. The advantage of including all those movements is that a more complete measure is obtained of actual arm use in daily life, as compared to only using specific activities (e.g. hair brushing, eating) or movements (e.g. reaching). To measure arm use, we developed and validated the accelerometer-based Activ8 arm use monitor (the Activ8-AUM), described in ***Chapter 5***. Although the use of accelerometry to measure arm use has limitations, it is currently the preferred technique due to the lack of other widely applicable and accepted techniques [44]. The main limitation of accelerometry is that it measures accelerations, i.e. movement, which makes it impossible to measure static arm use, such as holding an object. Moreover, arm movements are neither essential nor sufficient for functional arm use. To minimize this latter problem, we defined arm use as *' … during sitting and standing'*, which excludes arm movements due to walking and other whole-body movements. In addition, we applied a threshold to the movement counts above which they are classified as arm use. Applying a threshold to accelerometry data proved successful in other studies [13, 45, 46]. The study in ***Chapter 5*** shows that, overall, the Activ8-AUM correctly detected 75% of arm use, although arm use without movement and non-use with movement were not so well classified. Unfortunately, the effect of including body postures & movements in the analysis of arm use has only been investigated to a limited extent. Until now, only one study has shown that the correlation of activity counts with the Box and Block test improved significantly when walking bouts were excluded [47].

The results of the study in ***Chapter 6*** show that data on arm use can be useful to assess functional recovery after a stroke. However, since that was a pilot study, future research needs to examine the recovery of arm use in larger groups, including important determinants of arm use recovery, e.g. neglect, apraxia, and received therapy. Another important determinant to be considered is arm dominance. Studies on patients with Complex Regional Pain Syndrome have shown that, whether or not the dominant arm or non-dominant arm was affected, had an impact on the amount of arm use [48, 49]. After stroke, when the restitution of arm use fails, recovery can result from compensational strategies [50]. The success of these strategies might be influenced by the fact that the dominant or non-dominant arm can be affected.

In order to use measurements of arm use to unravel the working mechanism of arm use recovery and to improve and personalize stroke rehabilitation, measurements may be improved by adding sensors that are based on technologies other than accelerometry. For example, Leuenberger et al. [47] used an inertial measurement unit to quantify functionally relevant arm use. This device combines an accelerometer, a gyroscope and a magnetometer and showed promising results; however, the high correlation with the Box and Block test was not better than the correlation with only accelerometry data when walking bouts were excluded. Another possible improvement could be the use of an individual and self-learning algorithm to detect the optimal threshold to distinguish between arm use and no arm use, based on movement counts measured by accelerometry.

GENERALIZABILITY OF THE RESULTS

In ***Chapter 6***, the arm use of people after stroke was assessed during the first 26 weeks after their stroke. The inclusion criteria were kept intentionally broad in order to increase generalizability, although people with severe mental and severe communication problems were excluded. People with severe communication problems were excluded due to practical reasons, i.e. it is important that participants of a clinical study understand both the aim of the research and their rights as a participant. Since this exclusion was based on a practical reason and not related to the research itself, the results might be generalizable to people with communication problems. However, the results are not generalizable to people with severe mental problems, e.g. with neglect or apraxia. This latter type of conditions influence a person's physical behavior (including arm use), possibly leading to other recovery patterns in both arm function and arm use.

CLINICAL IMPLICATIONS OF THIS THESIS

This thesis investigated important aspects of measuring physical behavior that need to be considered when applying these measurements in clinical practice. The need to measure physical behavior in clinical practice was described in the section 'Physical Behavior: Application'. Routine assessments are not only important in stroke rehabilitation but throughout clinical practice. In general, it can personalize care, just like all other variables which are measured to determine a personal treatment plan. However, when information on physical behavior is used in clinical practice, it needs to be regularly assessed. A change in physical behavior should be a trigger to evaluate the reason for that changed behavior and to (possibly) change the treatment plan. For example, the results presented in ***Chapter 6*** show that, in daily life, arm use does not always recover in a straight line upwards. By regular assessment of arm use, non-use of the arm can be detected and tackled during, e.g., hand therapy. This early approach may prevent learned non-use on the longer term.

FUTURE RESEARCH

The previous sections made some recommendations for future research on specific issues. It is important to continue developing the field of measuring physical behavior because of its relationship with health research and the importance of measuring physical behavior during stroke rehabilitation. The working mechanism of physical behavior and the health effects of changed physical behavior, both positive and negative, need more in-depth study. Hopefully, new insights will allow to further optimize guidelines for a healthy lifestyle and interventions in stroke rehabilitation. Moreover, the development and validation of activity monitors need to be continued, with a focus on devices suitable for application in clinical practice. Therefore, developers need to collaborate with caregivers and patients about the requirements, needs, and wishes for such devices. Additionally, the potential of activity monitors to provide feedback on physical behavior should be investigated and developed. Feedback can be used as an important element of interventions aimed at improving physical behavior in both the general population as well as in rehabilitation populations.

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Summary

Measuring physical behavior after stroke is the main topic of this thesis. The general introduction in ***Chapter 1*** describes what physical behavior is and some of its components, i.e. sedentary behavior, body postures & movements, and arm use. Each of these components are introduced in relation to people after stroke, which was the study population in this thesis. In general, measuring physical behavior remains a challenge because it involves measuring a person's behavior in daily life. A suitable technique to objectively measure physical behavior is accelerometry. This is a relatively inexpensive and widely used technique in various activity monitors. With the use of activity monitors, a person can be continuously measured while he/she is freely moving in his/her own environment in everyday life. However, before applying these activity monitors, this thesis aimed to investigate two methodological aspects of measuring physical behavior from the perspective of stroke rehabilitation. Thereafter, an activity monitor was used to measure daily-life arm use during stroke rehabilitation.

Sedentary behavior, one of the components of physical behavior, is defined as '*any waking behavior characterized by an energy expenditure ≤1.5 METs while in a sitting reclining, or lying posture*'. However, most earlier studies investigating sedentary behavior measured only one component: either 'the amount of time someone sits' or 'the amount of time having a low energy expenditure'. Since it was unclear what the effect is of applying different operationalizations of sedentary behavior, this issue was investigated in ***Chapter 2***. In that study, we compared sedentary behavior operationalized as 1) sitting/reclining/lying, 2) low energy expenditure, and 3) the combination of both according to the definition. The results show that different operationalizations of sedentary behavior have a significant effect on the outcomes of sedentary behavior, e.g. total sedentary time, and the way sedentary time is accumulated in bouts. The differences between these operationalizations are large enough to be relevant, i.e. sedentary time differed by 15% and accumulation variables by almost 50%.

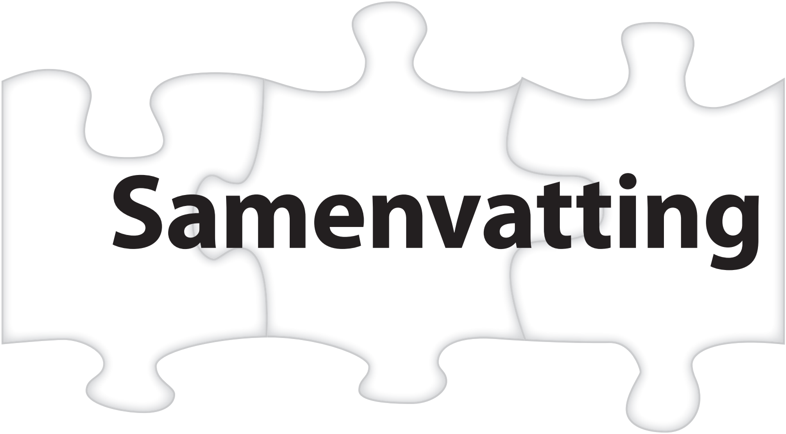
In addition to the study among healthy people, in ***Chapter 3*** we assessed the effect of the three operationalizations of sedentary behavior in people after stroke. The rationale for this follow-up study was that the frequency and the duration of both sitting and having a low energy expenditure are most likely to differ between people after stroke and healthy people. Therefore, the results of the study in ***Chapter 2*** may not be generalized to people after stroke. Moreover, in this population, it is important to decrease sedentary behavior because of their increased risk for cardiovascular disease and their possibly increased sedentary behavior due to motor problems caused by the stroke. The results of this follow-up study are comparable (with the same order of magnitude) with those of the study in healthy people, i.e. the operationalization of sedentary behavior has a significant effect on the outcomes of sedentary behavior.

Although accelerometer-based activity monitors can be used to measure physical behavior and many of these devices are commercially available, most are unable to measure body postures & movements. Measuring this component of physical behavior is important for people after stroke in order to assess functional status and motor recovery. The commercially available physical activity monitor 'Activ8' (30x32x10 mm; 20 g) is a one-sensor, accelerometer-based monitor that classifies body postures & movements, as well as their intensities. It is a device with considerable potential for use in clinical practice due to its additional features, including the ability to provide feedback, and the communication platform for caregivers and consumers. However, before using this device, it was important to assess its validity to measure body postures & movements, as presented in ***Chapter 4***. The results of that study show that the agreement between the Activ8 and the video reference data was sufficiently high to validly apply this activity monitor in stroke rehabilitation.

Measuring arm use is less common than measuring physical activity and sedentary behavior, possibly due to the lack of commercially available devices. Using accelerometry to measure arm use has one limitation: *arm movements* are measured instead of *arm use*, which is not the same thing. For instance, arm movements due to walking (e.g. arm swing) differ in terms of functionality from arm movements in a sitting or standing posture. Nevertheless, we used the Activ8 to develop an arm use monitor, because it is easy-to-use, comfortable to wear, and relatively inexpensive. ***Chapter 5*** describes the development and validation of the Activ8 arm use monitor (the Activ8-AUM). This monitor consists of three Activ8s: one attached to the unaffected thigh and the other two to each wrist. During the data analysis, we applied two principles to overcome the limitation of using accelerometry. First, we applied a threshold to the movement counts: small, less intense movements are categorized as no arm use, and more intense movements are categorized as arm use. Second, we used data on body postures & movements of the leg sensor to distinguish between arm movements during lying/sitting and standing, and arm movements during other body postures & movements. Results of the study in ***Chapter 5*** show that, after a stroke, the Activ8-AUM measured arm use sufficiently correctly to allow this arm use monitor to measure physical behavior.

During stroke rehabilitation, a person's ultimate goal is to restore actual arm use in daily life. However, since the ability to move and use the arms is not exactly the same as actually using them, it is important to assess actual arm use in daily life, as well as arm function. The Activ8-AUM was applied in people after stroke to measure recovery of arm use and its relation with recovery of arm function during the first 26 weeks after the stroke. The results of this study are presented in ***Chapter 6***. Arm use was measured at 3, 12, and 26 weeks after a stroke and was operationalized as the ratio of both arms; i.e. *'the* *movement counts of the affected arm divided by the movement counts of the unaffected arm’*. During the 26 weeks, there was a significant increase in the arm use ratio, although the ratio was low and dominated by the unaffected arm as compared to the reported ratio in healthy people. The arm use ratio seemed to be nonlinearly related with arm function, which was measured with the Fugl-Meyer Assessment. People with a better arm function had a more symmetrical arm use, although this was clearer in the higher arm functions. This nonlinear nature may indicate that a certain level of arm function is needed before the arms will be used in a more symmetrical way.

Chapter 7, the general discussion, summarizes and discusses the main findings of this thesis. These findings are discussed from two main perspectives: the different methodological aspects of measuring physical behavior, and the different components involved in physical behavior. These two perspectives are addressed from both a general and a stroke-specific viewpoint. Finally, the generalizability of these studies and their potential clinical implications are discussed, and some recommendations for future research are made.



Samenvatting

Het meten van beweeggedrag na een beroerte is het hoofdonderwerp van dit proefschrift. ***Hoofdstuk 1***, de algemene inleiding, beschrijft wat beweeggedrag is en uit welke componenten het bestaat, o.a.: sedentair gedrag, lichaamshoudingen & –bewegingen, en armgebruik. Deze componenten van beweeggedrag worden besproken in relatie tot mensen die een beroerte hebben gehad – de studiepopulatie in dit proefschrift. Het meten van beweeggedrag is over het algemeen een uitdaging omdat het gaat om het meten van menselijk gedrag in het dagelijks leven. Om dit gedrag objectief te meten, kunnen versnellingssensoren worden gebruikt. Deze sensoren zijn relatief goedkoop en worden veel gebruikt in activiteitenmonitors. Met deze monitors worden mensen continue gemeten terwijl ze, ongehinderd en in hun eigen omgeving, hun dagelijkse bezigheden uitvoeren. Het doel van dit proefschrift is het onderzoeken van twee methodologische overwegingen bij het meten van beweeggedrag na een beroerte. Tevens is een activiteitenmonitor gebruikt om armgebruik in het dagelijks leven te meten tijdens de revalidatie na een beroerte.

Sedentair gedrag is een component van beweeggedrag en is gedefinieerd als '*gedrag in een wakkere toestand met minimaal energiegebruik (≤1.5 METs) terwijl men zich in een zittende, achteroverleunende of liggende positie bevindt'*. Eerdere onderzoeken naar sedentair gedrag maten vaak slechts één component: 'de tijd dat iemand zit' of 'de tijd dat iemand minimaal energie gebruikt'. Omdat het niet duidelijk is wat het effect van deze keuze is, hebben wij in ***Hoofdstuk 2*** het effect van verschillende operationalisaties van sedentair gedrag onderzocht. In dat onderzoek was sedentair gedrag geoperationaliseerd als 1) zitten/achteroverleunen/liggen, 2) laag energiegebruik, en 3) de combinatie van beide componenten zoals in de definitie beschreven. De resultaten laten zien dat verschillende operationalisaties van sedentair gedrag een significante invloed hebben op de uitkomsten van het sedentair gedrag. Gebruikte uitkomstmaten waren de sedentaire tijd en maten die de opbouw van deze tijd in periodes beschrijven. De verschillen tussen operationalisaties zijn dusdanig groot, dat ze ook relevant waren. Sedentaire tijd was 15% en de manier van opbouw bijna 50% verschillend tussen de operationalisaties.

In aanvulling op het onderzoek met gezonde mensen, hebben we in ***Hoofdstuk 3*** het effect van de eerder genoemde operationalisaties onderzocht bij mensen die een beroerte hebben gehad. De reden voor dit vervolgonderzoek was dat zowel de frequentie als de duur van zitten/achteroverleunen/liggen en een laag energie verbruik anders kunnen zijn bij mensen die een beroerte hebben gehad. Daarom zijn de resultaten van ***Hoofdstuk 2*** niet automatisch toepasbaar in deze patiëntengroep. Daarbij is het bij mensen na een beroerte belangrijk om sedentair gedrag te verminderen vanwege een verhoogd risico op cardiovasculaire ziekten en een mogelijk verhoogde sedentaire gedrag door de motorische problemen als gevolg van hun beroerte. In dit onderzoek hebben we vergelijkbare resultaten gevonden als bij het onderzoek met gezonde mensen: de operationalisatie van sedentair gedrag was in gelijke mate van invloed op de uitkomsten van sedentair gedrag.

Zoals eerder aangegeven, kunnen activiteitenmonitors gebaseerd op versnellingssensoren worden gebruikt om beweeggedrag te meten. Er zijn vele activiteitenmonitors commercieel beschikbaar, maar de meeste zijn niet geschikt voor het meten van houdingen & bewegingen. Het meten van deze component van beweeggedrag is echter belangrijk voor het beoordelen van de functionele status en het motorisch herstel bij mensen na een beroerte. De 'Activ8' (30x32x10 mm; 20 g) is een activiteitenmonitor, gebaseerd op versnellingssensoren, die houdingen & bewegingen en bewegingsintensiteit meet. Deze monitor is commercieel verkrijgbaar en bestaat uit slechts één unit. Het is een veelbelovend apparaat voor het meten van beweeggedrag in de klinische praktijk door zijn extra functies zoals het geven van feedback en het aanbieden van een online communicatie portaal voor zorgverleners en gebruikers. Echter, voordat deze monitor kan worden gebruikt, is het belangrijk om de validiteit van de meetresultaten te onderzoeken, dit is beschreven in ***Hoofdstuk 4***. Resultaten van dit onderzoek laten een dusdanige overeenkomst zien tussen de Activ8 en referentiedata afkomstig van video-opnames dat deze activiteitenmonitor valide is voor het meten van houdingen & bewegingen tijdens revalidatie na een beroerte.

Het meten van armgebruik in het dagelijks leven wordt veel minder gedaan dan het meten van algehele fysieke activiteit en sedentair gedrag. Dit kan komen door de afwezigheid van commercieel beschikbare monitors die armgebruik kunnen meten. Het gebruik van versnellingssensoren voor het meten van armgebruik heeft een nadeel, namelijk dat *beweging* wordt gemeten en niet *gebruik*. Armbewegingen tijdens lopen (de armzwaai) verschillen bijvoorbeeld functioneel gezien van bewegingen tijdens zitten of staan. Ondanks deze beperking, hebben we de Activ8 gebruikt voor het ontwikkelen van een monitor om armgebruik te meten in het dagelijks leven. Deze monitor is namelijk makkelijk in het gebruik, comfortabel om te dragen en relatief goedkoop. ***Hoofdstuk 5*** beschrijft de ontwikkeling en validatie van de Activ8 arm use monitor (Activ8-AUM). Deze monitor bestaat uit drie Activ8's: één op de voorkant van het niet-aangedane bovenbeen en de anderen elk om een pols. Om de eerder genoemde beperking van versnellingssensoren te minimaliseren hebben we twee maatregelen genomen. Als eerste hebben we een drempelwaarde toegepast zodat kleine niet-intensieve bewegingen niet als armgebruik worden gezien. Als tweede hebben we gebruik gemaakt van de informatie van houdingen & bewegingen gemeten met de beensensor. Hiermee hebben we armbeweging tijdens liggen/zitten en staan gescheiden van armbewegingen tijdens andere houdingen & bewegingen. De resultaten van het validatiegedeelte laten zien dat deze eenvoudige Activ8-AUM voldoende valide armgebruik meet bij mensen die een beroerte hebben gehad en dus kan worden toegepast om beweeggedrag te meten.

In de revalidatie na een beroerte is het ultieme doel om het armgebruik in het dagelijks leven tot een functioneel niveau te herstellen. Omdat de capaciteit voor het bewegen van de arm en dus het potentieel gebruiken van de arm niet hetzelfde is dan het daadwerkelijk ook doen, is het werkelijke armgebruik in het dagelijks leven belangrijk om te meten naast de armfunctie. In ***Hoofdstuk 6*** is de Activ8-AUM gebruikt om het herstel van armgebruik te meten bij mensen die een beroerte hebben gehad en dit te relateren aan armfunctie. Armgebruik is in dit onderzoek gemeten op 3, 12 en 26 weken na de beroerte en is geoperationaliseerd als *'de ratio van het armgebruik van de aangedane zijde ten opzichte van het armgebruik van de niet-aangedane zijde'*. Gedurende de eerste 26 weken na een beroerte steeg de ratio van het armgebruik significant, maar bleef het laag en gedomineerd door de niet-aangedane arm in vergelijking met literatuur gegevens van gezonde mensen. De ratio van armgebruik leek niet-lineair gerelateerd aan armfunctie, die gemeten werd met de Fugl-Meyer Assessment. Mensen met een betere armfunctie hadden een meer symmetrisch armgebruik, hoewel dit verband duidelijker was bij een hogere armfunctie. Deze niet-lineaire aard lijkt aan te geven dat er een zekere armfunctie nodig is voordat de armen meer symmetrisch worden gebruikt.

Hoofdstuk 7, de algemene discussie, beschrijft en bediscussieert de belangrijkste bevindingen van dit proefschrift. Als eerste wordt dit beschreven vanuit het perspectief van verschillende methodologische overwegingen bij het meten van beweeggedrag. Als tweede worden verschillende componenten van beweeggedrag bediscussieerd. Beide perspectieven worden in het algemeen en beroerte-specifiek besproken. Tevens worden de generaliseerbaarheid en de klinische betekenis besproken en worden suggesties gedaan voor toekomstig onderzoek.

Dankwoord

Aan alles komt een einde, zo ook aan mijn promotie en aan dit boekje. Hier aan het eind wil ik graag iedereen bedanken die mij op welke manier dan ook heeft geholpen om dit proefschrift tot stand te laten komen. Iedereen die zijn naam niet in dit dankwoord ziet terugkomen, ben ik even dankbaar als de mensen die ik persoonlijk bedank.

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The author

CURRICULUM VITAE

Malou Fanchamps was born on August 8, 1987 in Kerkrade, the Netherlands. She graduated in 2005 from secondary school (VWO) at College Rolduc in Kerkade. The same year she started studying Biomedical Sciences at the Radboud University. After obtaining her Bachelor's degree in 2008, she continued with a Bachelor of Medicine from which she graduated in 2010. At the department of Neuro-Otology of the University Hospital Basel (Switzerland), she assessed the early detection of balance disorders in mildly affected patients with Multiple Sclerosis under supervision of Prof. dr. John Allum. In 2013, she finished her Master Biomedical Sciences with Human Movement Sciences as specialization at the Radboud University. Her Master's thesis was about using fNIRS to measure brain activity during dual tasks in healthy subjects and patients with Parkinson's Disease at the department of Geriatrics of the Radboudumc under supervision of Prof. dr. Marcel Olde Rikkert. In March 2013, Malou started working as lecturer Human Movement Sciences at the Maastricht University. In June 2014, she started working on the research described in this thesis at the department of Rehabilitation Medicine of the Erasmus MC under the supervision of Prof. dr. Henk Stam and Dr. Hans Bussmann. Currently, Malou works at the Brain Foundation Netherlands (Hersenstichting). She works on projects contributing to the Brain Foundation's mission to prevent, diminish and stop the burden of brain disorders, in order to live longer with a higher quality of life.

LIST OF PUBLICATIONS

Fanchamps MHJ, Selles RW, Regterschot GRH, Boers L, Meskers CGM, Ribbers GM, Stam HJ, Bussmann JBJ. Recovery of objectively measured daily-life arm use after stroke and its relationship with arm function. *Submitted*

Fanchamps MHJ, de Kam D, Sneekes EM, Stam HJ, Weerdesteyn V, Bussmann JBJ. Effect of different operationalizations of sedentary behavior in people with chronic stroke. *Disabil. Rehabil.* **2018**; Nov 26: 1-7.

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PhD PORTFOLIO

Summary of PhD training and teaching

Name PhD student: M.H.J. Fanchamps	**PhD period:** 2014-2017
Erasmus MC Department: Rehabilitation Medicine	**Promotor(s):** Prof. dr. H.J. Stam
Research School: -	**Supervisor:** Dr. J.B.J Bussmann

1. PhD training	**year**	**ECTS**
General courses		
- Scientific English	2016	3
- Scientific Integrity	2016	0,3
- Systematic Literature Retrieval in PubMed	2017	0,3
Seminars and workshops		
- PhD day, Rotterdam	2015	0,2
- PhD day, VvBN	2015	0,3
- MedTech West meeting	2015	0,2
- VvBN meeting: "Hoe (on)gezond is zitten?"	2015	0,1
- VvBN meeting: "Bewegen en ICT/mHealth"	2015	0,1
- PhD day, Rotterdam	2016	0,2
- PhD day, VvBN	2016	0,3
- VvBN Symposium	2017	0,3
- PhD day, VvBN	2017	0,3
(Inter)national conferences		
- IMDI Neuro control Symposium, Egmond aan Zee, NL	2016	0,6
- ICAMPAM conference, Bethesda, VS	2017	1
Presentations		
- Presenting progress of PhD, research meetings department of rehabilitation medicine, Erasmus MC	2015	0,6
- Poster presentation: IMDI Neuro control Symposium	2016	0,3
- Poster presentation: ICAMPAM 2017	2017	0,3
- Presenting progress of PhD, research meetings department of rehabilitation medicine, Erasmus MC	2017	0,9
Other		
- Participating in research meetings department of rehabilitation medicine, Erasmus MC	2014	0,7
	2015	1,4
	2016	1,1
	2017	0,9
- Participating in lab meetings motor neuro rehabilitation	2017	0,7
- Organising PhD day, VvBN	2017	1,4
- Board member Physical Activity Community Erasmus MC	2017	0,7

2. Teaching		
Lecturing		
- Lecture Physical activity outcomes	2014	0,3
- Lecture Physical activity outcomes	2015	0,2
- Lecture Determinants physical activity	2015	0,3
- Lecture Physical activity outcomes	2016	0,1
- Lecture Determinants physical activity	2016	0,2
- Lecture Physical activity outcomes	2016	0,1
- Lecture Determinants physical activity	2017	0,1
Other		
- Supervising literature review medical students	2015	0,3
- Review presentations students clinical technology	2015	0,2
- Supervising 3 students human movement technology	2015	1,1
- Supervising 2 students TU Delft	2015	0,4
- Supervising 2 students human movement technology	2015	1,4
- Review presentations students clinical technology	2016	0,2
- Review presentations students clinical technology	2017	0,2