Actigraphy in evaluation and follow up of physical functioning of older adults

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VTT

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Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Tietotalo building, room TB109 , at Tampere University of Technology, on the 15th of December 2017 at 12 noon.

Abstract

For older adults, physical functioning status describes how well a person is able to manage necessary daily activities independently. Different tools exist for testing and follow-up of physical functioning state at different levels of health and age. However, technologies have not been widely adapted for monitoring the physical functioning status during daily life in a longitudinal setup.

In this thesis, the actigraph's characteristics for evaluating the physical functioning of older adults at various levels of health and functioning are studied. An actigraph measures activity level estimates continuously and is typically worn on the wrist for extended periods. The actigraph is a mature technology that has been used in the sleep research since 1970s. In addition to sleep patterns, the actigraph can assess a subject's physical activity levels, and sleep-wake rhythms. Furthermore, a novel processing concept for evaluating long-term activity pattern responses to external stimuli, such as facility's common activities or weather has been developed in this thesis.

This thesis utilizes three different datasets in which actigraph data have been collected online, parallel with physical functioning estimates. The first dataset includes subjects from a nursing home with intermediate to demanding care need, the second dataset subjects are assisted living residents who are mostly independent but might receive some support services, and the third dataset subjects are from a demanding nursing home unit. The third dataset includes longitudinal data (over three years at longest). In addition, a fourth dataset was used to compare the actigraph processing methods between a traditional actigraph and the online actigraph to understand how well the encountered results with datasets 1–3 could be generalized.

According to the results, at least a one-week-long period of actigraph recordings should be used in different processing methods to minimize the error in the monitored parameters (for example, sleep patterns and activity rhythms) when point measures are inspected. When the traditional actigraphs and the online actigraph were compared, especially activity rhythm estimates generalize well for the online actigraph measurement.

In the thesis, the actigraph estimates for sleep, activity level and diurnal rhythms are compared with physical functioning results by utilizing datasets 1–3. In combined data from datasets 1 and 2 (demented subjects were excluded from

the analysis) higher physical functioning estimate (activities of daily living assessment) was associated with higher physical activity level and with more night-time activity variance. In addition, subjects with better functioning tend to have more similar activity rhythms with the facility activities (novel concept) and less-stable day-to-day activity patterns. In Dataset 3 (now including subjects with and without dementia) better physical functioning was associated with more stable and stronger diurnal activity rhythm. However, the correlation between the diurnal rhythm stability and physical functioning might be explained by the severity of dementia according to the results. In the longitudinal case analysis, most of the activity rhythm patterns were associated with physical functioning changes as expected according to cross sectional analysis. In Dataset 2, the amount of time the subjects spent outside the facility correlated positively with better physical functioning. This suggests that different context information can provide meaningful information on the older adults' health in addition to traditional actigraph estimates.

Since the correlations slightly differed depending on the study population we suggest that monitoring activity level, activity rhythm strength, similarity and variability simultaneously is recommended. Sleep patterns were not connected with physical functioning in the utilized datasets. The thesis results suggest that the actigraph is a feasible health monitoring concept to be utilized in assisted living and nursing home settings and is suitable for follow up of changes in activity patterns associated with changes in physical functioning.

Tiivistelmä

Ikääntyneiden toimintakyky kuvaa heidän mahdollisuuksiaan itsenäiseen suoriutumiseen ja kapasiteettia osallistua erilaisiin aktiviteetteihin yhteiskunnassa. Toimintakyvyn testaamista varten on olemassa lukuisia menetelmiä eri elämänvaiheisiin. Vielä ei kuitenkaan ole hyviä työkaluja jatkuvaan toimintakyvyn mittaamiseen ja arviointiin arjen lomassa.

Tässä väitöskirjassa tutkitaan aktigrafian mahdollisuuksia arvioida ikääntyneen henkilön toimintakykyä. Aktigrafi on kellomainen laite, joka mittaa käyttäjänsä fyysistä aktiivisuutta pitkäkestoisesti. Aktigrafiaa on käytetty erityisesti unitutkimuksessa jo 1970-luvulta asti. Unen keston ja laadun arvioinnin lisäksi sillä voidaan seurata käyttäjänsä aktiivisuuden määrää ja aktiivisuuden vuorokautista rytmisyyttä. Väitöskirjassa on lisäksi selvitetty aktigrafian mahdollisuutta arvioida henkilön käyttäytymismuutosta johonkin ulkoiseen ärsykkeeseen, kuten laitoshoidon palvelurytmiin tai sään vaihteluihin.

Väitöskirjan analyysit perustuvat kolmeen tutkimusaineistoon. Kaksi aineistoa koostuu laitoshoidon asukkaiden ja yksi palveluasumisen asiakkaiden rekisteröinneistä. Toinen laitoshoidon aineistoista sisälsi pitkittäisrekisteröintejä useamman vuoden ajalta. Väitöskirjassa hyödynnettiin lisäksi neljättä aineistoa tutkimuksissa käytetyn aktigrafin (Vivago) tulosten yleistettävyyden arvioimiseksi.

Tulosten mukaan aktigrafimittausten tulisi olla lyhimmillään viikon mittaisia luotettavien mittaustulosten (esimerkiksi uni ja aktiivisuus) saavuttamiseksi. Tutkimuksissa käytetyn aktigrafin havaittiin vastaavan perinteistä aktigrafia erityisesti arvioitaessa käyttäjän aktiivisuus- ja unirytmejä.

Väitöskirjassa havaittiin useamman aktigrafian tunnusluvun olevan yhteydessä muilla menetelmillä (kyselyt ja toiminnalliset testit) arvioituun toimintakykyyn. Heterogeenisessa vanhusväestössä korkeampi toimintakyky assosioitui korkeampaan aktiivisuustasoon sekä päivä- että yöaikana. Lisäksi paremman toimintakyvyn omaavat henkilöt toteuttivat asumiskohteen keskimääräisiä aktiviteetteja paremmin kuin heikommassa kunnossa olevat. Homogeenisemman laitoshoidon ryhmän aineiston mukaan toimintakyvyn matalampi taso assosioitui heikompaan ja rikkonaisempaan vuorokautiseen aktiivisuusrytmiin. Myös erilaisiin konteksteihin liittyvät havainnot aktigrafissa, kuten ulkoilut, voivat kertoa tulosten mukaan henkilön toimintakyvyn tasosta objektiivisesti.

Koska aktigrafista laskettavien tunnuslukujen ja toimintakyvyn yhteys on joiltain osin riippuvainen kohderyhmän terveydentilasta, on suositeltavaa seurata rinnak-

kain henkilön aktiivisuustasoa, aktiivisuusrytmin samankaltaisuutta, voimakkuutta ja yhtenäisyyttä, jotta mahdolliset terveydelliset muutokset voidaan havainnoida ennakolta. Unikäyttäytymisen ja toimintakyvyn välillä ei havaittu systemaattista yhteyttä. Tulosten mukaan aktigrafian avulla seurattavat käyttäytymissuureet voivat luotettavasti indikoida terveydentilaa ja siinä tapahtuvia muutoksia.

Preface

The research presented in this thesis was conducted at VTT Technical Research Centre of Finland between 2006 and 2017. During those years I have had the privilege to work with very talented researchers at VTT and at different research partners.

I would like to thank Adjunct Professor Ilkka Korhonen for working as my supervisor and instructor and providing great help and guidance throughout the entire thesis project. I wish to thank PhD Juha Pärkkä with whom I worked during the first study related to the thesis topic. In addition to Juha and Ilkka, I'm grateful to Adjunct Professors Mark van Gils and Jyrki Lötjönen for insightful discussions related to my thesis work.

I would also like to thank Associate Professor Alpo Värri for supervising and instructing my thesis work. I owe thanks to my thesis pre-examiners PhD Jussi Virkkala and Professor Timo Jämsä for their thorough and thoughtful comments.

I would like to express my gratitude to MD, PhD Petteri Viramo for all the cooperation and guidance during the study at Oulu Deaconess Institute. I would also like to thank MD Ari Saarinen's help in sleep analytics and PhD Paula Paavilainen's understanding in elderly care aspects during the first study related to the thesis topic.

Moreover, I would like to thank PhD Elina Mattila and MSc Kari Antila for all the support on my thesis. I'm thankful for PhD Miikka Ermes and Lic Johan Plomp who have encouraged and aided me during my thesis work. I'm also grateful for PhD Tuula Petäkoski-Hult for advising me in the physical functioning topic from physiotherapy perspective during my work at VTT.

Many thanks also to Vivago's personnel for providing me all the technical and practical help during the studies in which my thesis work have been involved. Also the financial support from Finnish Cultural Foundation and TEKES is gratefully acknowledged.

Last but not least I want to thank my family and friends for all the strength and understanding they have shown me during this work. My two daughters, Juuli and Teresa, have given me joy, energy and love during the last years of this quest.

Oulu, November 2017
Juho Merilahti

List of publications

This thesis is based on the original research published in the following articles (referred in text as Studies II, V, VI) and conference papers (I, III, IV) between years 2007 and 2016. The publications are reproduced with kind permission from the publishers.

I   Merilahti, J., Saarinen, A., Pärkkä, J., Antila, K., Mattila, E., Korhonen, I. Long-term subjective and objective sleep analysis of total sleep time and sleep quality in real life settings (2007) Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings, art. no. 4353514, pp. 5202-5205.

II   Merilahti, J., Pärkkä, J., Antila, K., Paavilainen, P., Mattila, E., Malm, E.-J., Saarinen, A., Korhonen, I. Compliance and technical feasibility of long-term health monitoring with wearable and ambient technologies (2009) Journal of Telemedicine and Telecare, 15 (6), pp. 302-309.

III   Merilahti, J., Pärkkä, J., Korhonen, I. Connections of daytime napping and vigilance measures to activity behaviour and physical functioning (2011) Proceedings of the 8th IASTED International Conference on Biomedical Engineering, Biomed 2011, pp. 433-439.

IV   Merilahti, J., Pärkkä, J., Korhonen, I. Estimating older people's physical functioning with automated health monitoring technologies at home: Feature correlations and multivariate analysis (2012) Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 7096 LNCS, pp. 94-104

V   Merilahti, J., Viramo, P., Korhonen, I. Wearable monitoring of physical functioning and disability changes, circadian rhythms and sleep patterns in nursing home residents (2016) IEEE Journal of Biomedical and Health Informatics, 20 (3), art. no. 7081384, pp. 856-864.

VI   Merilahti, J. and Korhonen, I., Association between continuous wearable activity monitoring and self-reported functioning in assisted living facility and nursing home residents (2016), Frailty Aging,5(4), pp. 225-232.

Author's contributions

Study I: The author participated in the study's data collection and monitoring of data quality. Author was responsible for the analysis and the writing of the article.

Study II: The author participated in the study's data collection and monitoring of data quality. The author managed feasibility questionnaire distribution and was responsible for the analyses and writing of the article.

Study III: The author was responsible for defining the objectives, processing of the data, analysis and writing of the article. The author participated in the data collection as in Study II.

Study IV: The author's role was similar to that in Study III.

Study V: The author participated in designing the study objectives and designing of data collection. The author was responsible for analysis and writing of the article.

Study VI: The author was responsible for defining the study objectives, processing of the data, analysis and writing of the article. The author was not involved in data collection of a sub-dataset included in Study VI (Dataset 1 later in thesis).

Contents

List of terms and abbreviations

Accelerometer	Electromechanical device which can measure acceleration forces
ACORR	Autocorrelation
ACT	Activity Level Estimate of actigraph, average of a certain time period such as daytime
Actigraph	Wearable device that collects person's activity level estimate continuously, for extended periods
Actigraphy	Time series of actigraphy data
ADL	Activities of Daily Living
AMPL	Amplitude of Cosinor Analysis
AWEKN	Number of Awakening during the night time
BMI	Body mas index.
CDR	Clinical Dementia Rating scale
Circadian rhythm	Rytmic phenomenan which follows earth's light dark cycle (that is 24 hours)
Count	Value of an actigraphy epoch, typically different actigraph products provide an arbitrary value for an epoch
CRS	Circadian Rhythm Strength
Dementia	Brain disease that effect on thinking and remembering capacity of a person
Double plotted actogram	Graphical presentation of actigraph data over a long period, x-axis are minutes for 48 hours and y-axis are for dates
Epoch	Actigraph's physical activity level estimate
GDS	Geriatric Depression Scale
HOUSE	Housing rhythm correlation
IS	Interdaily Stability
IV	Intradaily Variability
MAE	Mean Absolute Error
MESOR	Mesor of Cosinor Analysis
MMSE	Mini Mental State examination

NAP	Total sleep time during daytime, napping time
Out of range	A feature of a telemetric actigraph which informs whether the actigraph device has been on the basestation range or not
P	Probability for a statistical model's null hypothesis
PHASE	Acrophase of Cosinor analysis
Physical functioning	Estimate of person's physical ability on performing different tasks such as walking
Poincare	Analysis method to study signals repeated similarities. Named after Henri Poincare.
Polysomnography, PSG	PSG is based on electroencephalogram, electro-oculogram and electromyogram. It is used to perform a sleep state analysis in clinical settings.
R	Pearson's correlation coefficient
RA	Relative amplitude
RAI	Resident Assessment Instrument
RHO	Spearman's rank correlation coefficient
SD	Standard Deviation
SE	Sleep Efficiency
Sleep onset	Timing of transition from wakefulness into sleep
Social alarm system	A device/system which is used to summon for help in an assisted living or nursing home settings
Telemetric actigraph	An actigraph system used in the thesis, which has wireless online connection with backend system (Vivago)
TST	Total Sleep Time
VO2MAX	Describes maximum aerobic capacity.
Zeitgeber	External stimulus which effects on the circadian rhythm system. Can be used to synchronize and strengthen the internal rhythm system. E.g. natural light.

1. Introduction

Development of health care, health-related information and modern society in general have resulted in longer lives. This ageing population in many Western countries has also brought the dilemma of how to make health and social care costs sustainable as the ratio between the working age population and older adults changes. Figure 1 is an example of how the proportion of people aged over 65 is predicted to increase dramatically until 2030 in Finland.

Number of children and elderly per 100 persons in working-age
Children (age under 15)   Elderly (age over 65)
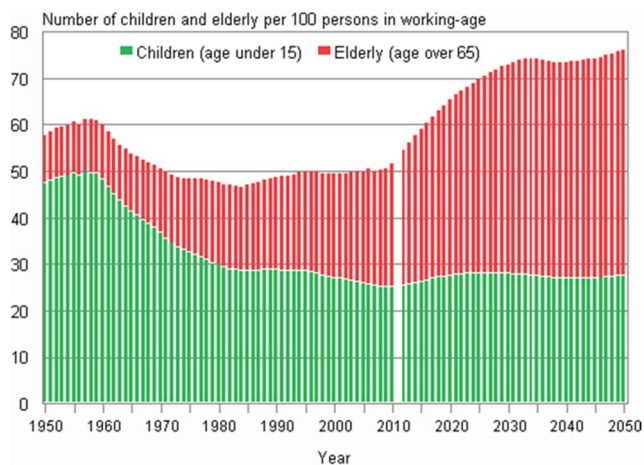
Figure 1: Demographic dependency ratio in 1950–2010 and projection for 2011–2050 (Official Statistics of Finland (OSF) 2010)

This progress is visible, for example, in the social care costs structure. The services for the older adults cover currently one third of all the social care cost, and the biggest expense is the pensions and other services for retired people. The next biggest share was the health care expenses covering 25 percent of the social costs. The cost development will most likely follow the population structure in the future if disruptive, new solutions cannot be found and taken into use.

The two most important aspects for controlling the social- and health care costs (Matikainen et al. 2004) are to enable some years longer work careers, i.e. mini-

mizing premature retiring, and to improve functioning of older people which would lead to improved independence and decreasing care need. There are other benefits that well-functioning older adults can contribute to society such as increased volunteer work and support for the younger generation (e.g. helping for children and grandchildren) in addition to social and health care saving. This type of a positive development would be beneficial as well for the individuals themselves from a quality of life and income perspective.

How would improved functioning be possible in old age? It has been conceptualized that ageing might be either "usual" where physical, social and cognitive functions are declined with age, or "successful" in which the functional decline is minimized with age and extrinsic factors play a neutral or positive role (Rowe and Kahn's model in (Bowling, Dieppe 2005). However biomedical research has focused more on studying "unsuccessful" ageing (impairment and illnesses) although the focus according to health politics will be on disease prevention and health promotion (Bowling, Dieppe 2005). For example, it has been suggested (Hujanen et al. 2004) that we should now focus on preventive care and other beneficial actions on people approaching retirement age, and on the proactive care of older people. It has also been reported that prevention and rehabilitation are very efficient in old age. However the focus of health politics is not to lengthen the age per se, but rather to maintain as good functioning and health status as possible to maximize work ability, independent living and good quality life years (Hujanen et al. 2004).

Many actions support the functioning in older age and every person has their individual needs and wills in the end which should be considered. In addition, different generations have different possibilities and backgrounds which should as well be considered when planning actions for enabling "successful ageing" (Heikkinen, Rantanen 2008). For example, it was noted that with higher internal mental resources (such as psychological factors, personality) one can compensate for the functional limitations, whereas lesser resources can aggravate the limitations (Femia, Zarit & Johansson 2001).

Since the focus should be on preventive and early actions, also the emphasis in the assessment of daily functioning should be focused on monitoring and assessment of the so-called preclinical functioning status of persons at risk (in this case an older adult). These data could lead to the proper actions for maintaining or even increasing the level of functioning (Fig. 2). For example, a need for "new ways of detecting decline in physical function, including ways that can be unobtrusive, yet accurately assess physical function and detect declines from an individual's normal functional performance" has been suggested (Rantz et al. 2012).

Physical functioning assessment is also an important tool when evaluating the care needs of a disabled (Heikkinen, Rantanen 2008, Cress 2006). The assessment results can be utilized, for example in screening, designing of interventions, rehabilitation planning and follow-up.

Activity behaviour has been documented to be an important factor in successful ageing and functioning (e.g. (Menec 2003)). In another way, knowing ones activity profile could facilitate the assessment of functional state or its development. Now-

adays, different low-cost technologies exist such as activity trackers, smart phones, pedometers or even novel computer controllers making it possible to record objectively a subject's activity behaviour during normal life. For example, body-worn movement sensors can distinguish a user's physical activity levels, analyse walking or running styles, quantify sleep patterns or guide a patient in rehabilitation. Most typically these solutions are based on accelerometer information which is further analysed to provide more meaningful and human-understandable information, for example based on extensive spectral content analysis. Another way to measure a subject's behaviour is to observe human biological processes and extract meaningful information from these data. For example, heart rate can be observed by measuring electric activity on the skin, by light absorption changes through the skin or by recording pressure changes the blood flow causes while we sit or lay down. Again, from the heart rate it is possible to follow the balance of one's nervous system or recovery from a physical activity. Even your mental state can be determined from your skin by measuring changes in conductivity due to sweat gland activity. As well, muscle activity tracking is nowadays reasonably easy with new smart textiles and electronics.

Ambient measurement technologies remove the subject's burden of wearing the technologies. With depth cameras, infrared sensors or floor sensors we are able to precisely track resident's behaviours and movements indoors where especially older adults with functional limitations tend to spend much of their time.

These new technologies and measures could potentially be utilized in functioning status assessment and monitoring. However the output they produce should speak the same language as the clinicians which is why they should "be validated against a battery of currently used – and widely accepted – techniques and indices" (Karnik, Mazzatti 2009). The clinicians and citizens should be aware of their limitations and possibilities. This requires well-designed studies, reporting of the required properties of these measurements and willingness to use the new tools in the field.
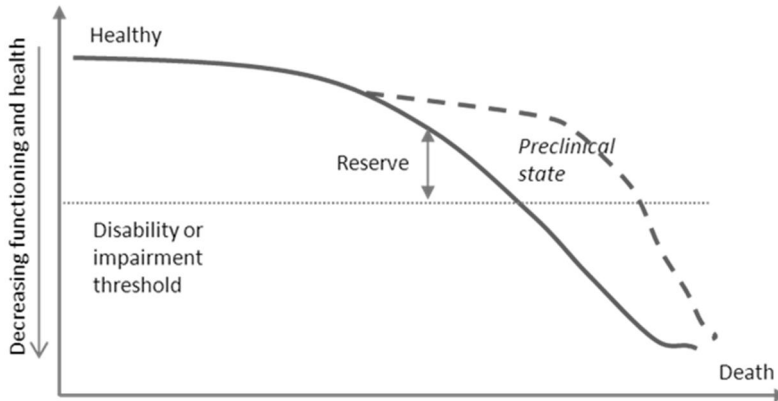
Figure 2: Progress of functioning during life. Dashed line describes "successful ageing" and solid line "usual ageing". Adopted from a related article (Cress 2006, Haveman-Nies, de Groot & van Staveren 2003).

1.1 Objectives

The objective of the thesis was to investigate if continuous, long-term activity monitoring can be used for unobtrusive estimation of physical functioning state and its changes in older adults. The studies applied a social alarm system (wrist-worn panic button) with an integrated activity sensor for estimating and monitoring of older user's physical functioning in various care settings over the long term, i.e. from some weeks to several years.

The specific objectives of the thesis were:

- To evaluate the feasibility and compliance of the social alarm system with activity monitoring in older users in their real daily environment (Studies II and V)
- To develop and optimize processing methods for long-term actigraphy data to quantify the wearer's habitual rest-activity (Studies IV–VI)
- To assess the validity of the actigraphy-based methods in quantifying the habitual rest-activity patterns (Studies I, III and IV)
- To assess the reliability and long-term robustness of the actigraphy processing methods with a test-retest setup (not published elsewhere)
- To assess the associations of actigraphy-based habitual rest-rest activity patterns with physical functioning of older adults and changes in it (Studies III–VI)

1.2   Outline of the thesis

Chapter 2 introduces a background of the physical functioning concept of older adults. The target is to give an overview on the theoretical model of the functioning in general and how the physical part is considered in the model. The second part of Chapter 2 presents statistics of physical functioning and impairments focusing on a population similar to that which is included in the thesis' material. The last part of Chapter 2 introduces assessment methods of physical functioning, and which characteristics of the methods need to be taken into account on these methods such as reliability and sensitivity.

Chapter 3 describes the objective activity monitoring method utilized (actigraphy) in the studies. The most typical habitual behaviours assessed by the actigraphy are presented including sleep, physical activity and daily rhythms. The related research on the reliability and feasibility on evaluating the habitual behaviours via actigraphy is discussed. The last part of Chapter 3 shows the current state of the art in research on assessing associations between physical functioning and long-term actigraphy monitoring for older adults via cross-sectional and longitudinal data.

Chapter 4 summarizes the results of the studies included in the thesis. At first the actigraph device utilized in the studies is described in detail. The second part of Chapter 4 lists the included datasets in the studies and presents the signal processing methods, which are applied with the actigraphy in the studies. The final part of Chapter 4 demonstrates the results on the measuring feasibility and reliability of the actigraph on assessing the behaviours in the long-term, and how these measures are associated with the physical functioning of older adults in assisted living and nursing home environments.

Chapter 5 includes the discussion of the results and evaluates the impact of the results in practise.

2. Physical functioning of older adults

In this chapter the physical functioning concept is introduced. The first section presents models of the physical functioning, the second section presents statistics related to physical functioning, and the third section presents the physical functioning assessment.

2.1 Definition and models of physical functioning

There are two major theoretical models for functioning, Nagi's (later updated by Jette and Verbrugge (Verbrugge, Jette 1994)) and the WHO's models (International classification of functioning, ICF (WHO 2015)). The newer Verbrugge and Jette's model is widely used in epidemiology and clinical research (Heikkinen, Rantanen 2008). Recently Jette (Jette 2009) suggested that the Nagi's model and its language and concepts should be replaced by the ICF (WHO) to allow universal disablement framework for research and care processes. He however reminded that although the terminology differs between the two models, the basic concepts under the surface are quite similar (Jette 2009). The WHO's model is presented in Figure 3.
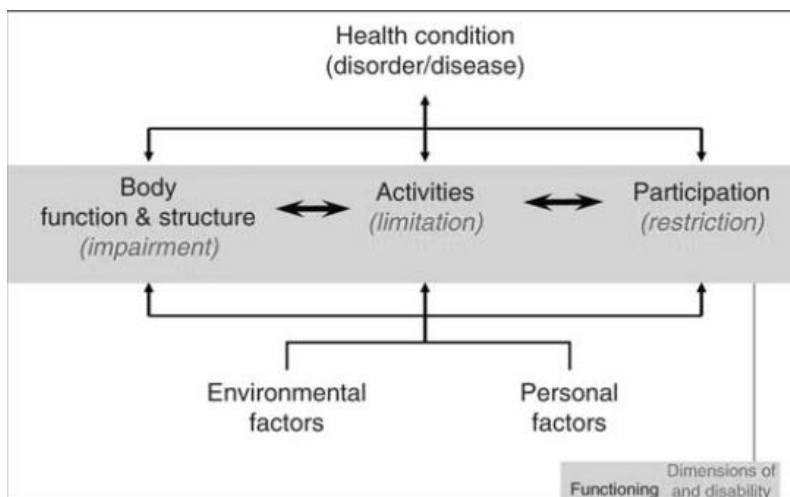
Figure 3: WHO's model of functioning, International Classification of Functioning (ICF).

The terms disability and functioning are key elements in ICF. Disability has been defined as a negative outcome between environmental requirements and a person's capacity, that is, a person who can no longer maintain their role in society. Disabilities can exist in different activities and daily functions. The functioning term can be considered as the opposite of disability (see Fig. 2, reserve) (Heikkinen, Rantanen 2008) and is categorized as several areas. Functioning is as well a lived experience by people (Bickenbach et al. 1999) meaning that it is not always easy to quantify. In the WHO's model (ICF) the functioning and disability consist of three parts: body function and structure, activities and participation, which have a dynamic interaction between various health conditions and contextual factors (environmental and personal, Fig. 3).

In the model the body functions and structures refer to physiologic functions and anatomic parts. The impairment is loss and deviation from the normal body functioning and structure. The categories of this part cover, for example, mental and neuromuscular functions, and structures of the nervous and cardiovascular systems. Activities describe a certain task execution and what kind of difficulties the person might have with them. The categories of the activities are, for example, related to the ability to carry objects. This part may be seen to describe the whole body functioning instead of a single organ or a system. Participation and restriction refers to involvement and experiences of an involvement in life situations. This part targets the description of whole-body ability in their complete environment, such as preparing meals or doing sports. The WHO's model is a so-called coherent biopsychosocial model of functioning (Jette 2009, Stucki, Kostanjsek & Cieza A. 2010) (Personal factors are not coded in the ICF. WHO-FIC Network Functioning and Disability Reference Group is exploring possibilities and methodological approaches to develop a classification of personal factors).

When considering the model in practise it suggests that the status and the development of the functioning and disability can be complex processes. For example, joint pains can decrease physical activity level which leads to decreasing muscle strength. This might further on emphasize the symptoms of impairment (joint pains) and effect on the physical activity amount. These causes can even further lead to isolation due to inability to go outside and meet friends which again can lead to depression. The domino effect is ready. Also, personal factors affect how disabling certain impairment is; mood and personality can determine how well a person can manage in society, for example, after an injury (Heikkinen, Rantanen 2008).

Hence, it would be beneficial to detect changes in some relevant aspect of functioning already in the early phases of degeneration (preclinical measures). This would enable settling of the possible reason behind the decline (for example an illness) and starting recovering actions faster. These preclinical measures are signs preceding the actual disabilities. Until the disease or some other condition affect daily functioning, self-reported functional measures can fail to show any functional limitations. The early actions would help in maintaining the reserve in the functioning status (Fig. 2) as fast negative changes are possible due to some health problems especially in old age(Heikkinen, Rantanen 2008). It was suggested, for example in (Cress 2006) that one of the future studies needed would be cognitive and physical markers of preclinical disability.

2.2 Statistics on physical functioning of older adults

In the US arthritis (30%), heart problems (23%) and hypertension (14%) were the three most common conditions behind functional limitations in 2001 for non-institutionalized people over 65 years. In Australia the three conditions causing the most common impairments were arthritis and related disorders (50%), hearing disorders (43%) and hypertension (38%) including institutionalized older adults as well. The percentages do not sum up to 100% due to co-morbidities. In the Australian study dementia and Alzheimer's disease covered 17 percent of disabilities. In Finland, when measuring disabilities at least in one daily activity (having major difficulties or not able to perform) the portion of disabled people for people over 65 years was 10.1%. For older adults of 85 years and over this portion was 35.8%. In the same report obesity (especially severe) was raised as a risk factor for disability endangering other positive developments of lowering disability prevalence. For example, it was noted that although in Finland the condition causing the impairments such as arthritis have decreased the other risk factors such as obesity and hypertension have been on the rise (Lafortune, Balestat 2007). However 20 % of disablement is in the absence of up to 15 of the most common chronic conditions (Cress 2006).

Higher cognitive performance and ability to generate power explain almost three quarters of the physical performance in older (Cress 2006). Dementias and difficulties in performing daily activities are key factors to differentiate community

dwelling older people from institutionalized ones (Heikkinen, Rantanen 2008). In Finland the portion of older adults living in care institutions is between 4 and 5 percent (Finne-Soveri 2012). Lifestyle factors such as inactivity, smoking, alcohol and obesity have been associated with the ability to perform daily activities. A vast amount of factors predicting coming disabilities already exist and it would be important to develop interventions lowering these risks for gaining more independent and functioning life years. (Heikkinen, Rantanen 2008)

2.3   Physical functioning assessment of older adults

In this section I describe the physical functioning assessment paradigm. The text is not intended to be an exhaustive description of the topic but rather an overview from the perspective of this thesis.

The functioning status is needed to screen, assess and objectively measure for primary and secondary prevention of disabilities (Cress 2006). The assessment methods are needed for discriminating between the functional status and change in that status at different stages of health and age since functioning changes throughout life as shown in Fig. 2. If we know which physiological and functioning aspects will predict coming disabilities we can target the right interventions to right persons (Cress 2006).

Two primary functioning assessment instruments are self-reports and performance-based measures. They have been shown to correlate moderately. If, for example, depression or dementia is present objective measures are more reliable and accurate (Cress 2006). In rehabilitation, for example, self-report measurements are widely accepted for factors which are hard to measure from an objective standpoint (well-being, pain, feelings or sensation) (Federici, Meloni 2012) .

Objective or performance-based functional tests measure movement and performance of the whole body and not just a single physiological system. By comparing the score to the reference values a professional can determine whether the results imply a disability risk. Important physiological systems to tests are muscle strength of different body regions, balance, different senses and reaction times, and nervous system controlling these parts (Heikkinen, Rantanen 2008). In the EUNAAPA project, nine different areas of functioning measures were identified: physical activity level, endurance, locomotion, balance, mobility, manual dexterity and gross motor coordination, muscular strength, common indexes and ADL (activities of daily living) (Frändin, Rydwik). For example, condition of respiratory and cardiovascular systems is important for maintaining a higher activity level longer, i.e. some tens of minutes. Locomotion deficits can influence negatively more advanced functioning such as social activities, shopping and household work (Heikkinen, Rantanen 2008). It was suggested that multiple-task measures with a summary score can be more sensitive in detecting change than single-task or multiple-task tests with no summary score (Cress 2006). The most common performance tests were reported to be walking tests (e.g. walking speed, task track, six-minute walking), timed up and go and sit-to-stand repetitions, carrying or pick-

ing up an object, balance, grip strength, PEF (peak expiratory flow), and combinations of these (Heikkinen, Rantanen 2008, Cress 2006, Frändin, Rydwik).

As pointed out the so-called preclinical measures have recently become an important concept of the assessment paradigm. For example, a person can report difficulties in moving outside which could eventually prevent them from going out. The assessment results of this group are situated between the ones with no problems and ones with some functional impairment. Preclinical measures have not been studied extensively (Heikkinen, Rantanen 2008).

Interviews and questionnaires (self-reports): These measures normally try to quantify how able a subject is to perform daily activities at home and in society. Typically questionnaires are assessing either basic functions such as feeding or toileting (PADL or BADL, personal or basic activities of daily living) or more complex activities such as shopping or household work (instrumental ADL) which are also measuring social and cognitive functioning in addition to physical performance. The assessment can be done via interview, phone interview or with a paper questionnaire. For research purposes it is important that subjects from every functioning status group are being represented. It was also reported that data given by subjects themselves or care giver/relative are almost equally accurate, dementia being the exception. The doctor assessment was considered to be worse if compared with self-reports or a care giver/relative reported according to studies. (Heikkinen, Rantanen 2008)

Functioning tasks included in the questionnaires are not equal, although they are often reported side by side. Sensitivity and dynamics of the assessment method has to be considered as there can be a huge difference in functioning status among the subjects, and the floor and ceiling effect can become a danger. Only objective measurement yields interval scale data, which are additive, reproducible, comparable, and suitable for further analyses, which cannot be applied to ordinal scale scores (Szilvia 2007). The test patterns and questionnaires typically used in Finland are the Barthel Index, different ADL/IADL questionnaires, Functional Independency Measure (FIM), Resident Assessment Inventory (RAI) and ICF core sets (Heikkinen, Waters & Brzezinski 1983) Objective measures and questionnaires have been found to correlate modestly (Cress 2006). When clinical depression and cognitive impairment are present the objective measures provide more reliable results than questionnaires (Cress 2006). Both measures have their place and the variance of the tests is very important due to the dynamic nature of the functioning.

2.3.1   Characteristics of physical functioning assessment instrument

There are certain requirements for functioning assessment instruments which are as well valid for monitoring instruments. Test-retest reproducibility, validity and sensitivity to change are fundamental considerations when choosing an instrument for assessing physical functioning (Cress 2006). In primary health care assessment of functional capacity has to be easy and quick to perform, standardisable,

affordable, safe, acceptable by the subjects, valid and reliable. Test-retest setup is utilized to study reliability of the (Heikkinen, Rantanen 2008).

According to Dishman (Dishman 2006) the method assessing physical activity should be reliable, valid, practical and noninterfering. Korhonen et al. reported that other important features for home health monitoring devices are robustness, reliability (technological), durability, unobtrusiveness, and look when applied to real use (Korhonen, Pärkkä & Van Gils 2003). Day-to-day variability in monitoring measurements (especially biological variance such as behaviours and performance) is a source of unreliability which limits the conclusions drawn according to findings (Baranowski et al. 2008). This supports also the paradigm of continuous monitoring of health and functioning when subtle changes need to be detected.

The assessment method has to be suitable for the person's functioning state to avoid "ceiling" or "floor" effects (Cress 2006), which was reported as problematic especially for the self-reported and interview measures (responders reporting easily best of worst scores). This might prevent detecting possible changes due to the intervention or declining health (Heikkinen, Rantanen 2008). As well, if estimates are incorrect the conclusions and hypothesis might be erroneous (Morgenthaler et al. 2007). When studying the validity of a measurement the difference between the studied method and "golden standard" should be reported since the correlation does not provide absolute performance information. If the reference measure is not considered as the "golden standard" the correlation is enough for quantifying the validity and reliability (Ancoli-Israel et al. 2003).

3. Objective measures of habitual activity and rest from wrist actigraphy

In this chapter I will at first introduce a wrist-worn actigraphy measuring modality. The second part of the chapter focuses on introducing the actigraphic monitoring from the functioning assessment instrument's perspective by reviewing the related literature.

3.1 Wrist actigraphy

The lightweight devices that record body movement for extended periods at the waist, wrist, and/or ankle are called actigraphs. Actigraphs have a movement sensor (most typically accelerometer) and internal memory to store the recorded activity for several weeks or even months. Typically the movements have been digitized to epochs of 15 s, 30 s or 60 s (Tryon 2012) from which the further actigraphic analysis basis on. However the methodologies how these epochs are generated vary between actigraph brands. For example one commonly used actigraph product (Actiwatch) takes a peak activity value of each second (sample rate of 32 Hz) and form a sum of each seconds for example 15 seconds (Te Lindert, Van Someren 2013b). Also widely used microelectromechanical systems can collect the accelerometric data for various sample rates (for example 50 Hz) and store these data to memory of the sensor unit. The collected, high sampled movement data can be further converted to epochs and further to sleep estimates (Te Lindert, Van Someren 2013a) or directly to sleep estimates (Van Hees et al. 2015).

The first actigraphs were developed already in the early 1970s but their utilization was limited until the 1980s (Ancoli-Israel et al. 2003, Berger et al. 2008). After this, actigraphs have become an important assessment tool in sleep research and sleep medicine (Sadeh 2011). The most typical application of the actigraphy is sleep analyses when polysomnography (PSG, the golden standard in sleep monitoring) recording is too cumbersome. PSG is based on electroencephalogram, electro-oculogram and electromyogram. According to these measurements a trained professional categorize 20- or 30-second period as different sleep stages (Hall 2010). The actigraphy has showed more than 90 % agreement and less than

40 % of specificity in sleep/wake classification with PSG (Sadeh 2011). It is important to note that actigraphy measures only movement and not sleep per se. The most typical way to store the recorded activity has been on one-minute intervals. The pre-processing of the activity signal differs between the manufacturers and for certain models the user is able to select the pre-processing functions. Since there is some variance in the formation of the one-minute activity epochs they are normally referred as "counts". The existing actigraphic devices have different mechanical properties and sensitivities. Typically the actigraphs have been used to measure sleep, activity levels and circadian rhythms.

It is not clear which wrist (dominant or non-dominant) is superior for actigraphs but both have found to yield high correlations and similar agreements of sleep/wake classification with PSG (Ancoli-Israel et al. 2003, Van Someren 2011). It was found that wrist placement were superior compared to trunk or ankle placement in some sleep studies (Ancoli-Israel et al. 2003). However superiority of actigraphy placement on different body parts is currently not established. There are artefacts in actigraphy, such as non-compliance, breathing originated or due to vehicle riding (Sadeh 2011) . It was also noted that when reporting the actigraph results detailed information on the algorithms and techniques should be specified (Morgenthaler et al. 2007).

Actigraphs are not the only possibility for recording sleep and physical activities in the long term. The other objective modalities often reported in literature are pedometers (i.e. step counters), accelerometers in smart phones or other devices, questionnaires and self-reports, calorimeters and heart rate monitors (Cress 2006)(Ong, Blumenthal 2010), (Cress 2006). Recently, different ambient technologies have been introduced in the assisted living environment from commercial (e.g. QuietCare, Intel-GE Care Innovations, California, USA) and research sides (Noury, Hadidi 2012, Dodge et al. 2012, Popescu, Mahnot 2012). All of the methodologies have their advantages and disadvantages. The most significant aspect from this thesis perspective for selecting the Vivago telemetric actigraphy was the ease of data collection since the system is already in wide use in various nursing homes and assisted living facilities in Finland. The next sections introduce measurements of the actigraph.

3.1.1   Sleep patterns from actigraphy

Typically actigraphs produce a sleep/wake classification for each minute with algorithms developed against PSG. Actigraphs are reported to more likely detect sleep than being awake, having thus low specificity, which should be considered when interpreting the results (Sadeh 2011). It was also noted that when PSG-based sleep efficiency diminished the actigraphy accuracy decreased (sleep efficiency = SE, percentage of time in sleep in bed) (Ancoli-Israel et al. 2003). For healthy adults actigraphy was reported to be valid for measuring sleep durations and sleep/wake activity patterns, but not very reliable for specific measures like sleep onset (Ancoli-Israel et al. 2003). In general, the actigraphy accuracy wors-

ens for subjects with more disturbed sleep which is often the case for older people (Ancoli-Israel et al. 2003, Sadeh 2011).

For insomniac patients who tend to have night-to-night sleep variations, actigraphy monitoring is considered beneficial due to its long-term monitoring character (Sadeh 2011). Actigraphy can as well be a better method to report awakening compared to self-reports with which some of the awakening can be missed (Hall 2010). Clinicians have also reported that self-reported sleep diaries might not be truthful and objective measurements should be encouraged (Van Someren 2011). It was suggested that actigraphy is potentially useful in long-term studies where detecting changes in sleep behaviour is of interest (Morgenthaler et al. 2007). For example, with 18-day-long PSG and actigraphy recordings the methods had high correlation (R=0.92, P< 0.01) (Morgenthaler et al. 2007). Aggregation over several nights stabilizes individual differences, and some measures required aggregation over seven days or even longer for reflecting individual differences (Van Someren 2007).

Actigraphy algorithms need to be developed for different populations and for different sleep behaviour such as for daytime sleep. For reliable sleep estimates it is important to record bedtimes, off-wrist periods and other unusual events.

Actigraphy has been reported to be particularly useful in studies involving older adults. It was found, for example, that 42% of night-time awakenings in a nursing home were associated with noise, light or incontinence care (Ancoli-Israel et al. 2003). An actigraphy's validity in the older adult population seems to depend on the subjects' health and impairment rate. This is mostly because ageing and its illnesses effect fragmentation of the sleep cycle and thus might affect the reliability of sleep pattern estimates. Night-to-night variability might be interesting information regarding an older subject's health. At least seven-day-long recordings are encouraged when studying older adults' sleep patterns (Van Someren 2011). It was concluded that an actigraph was not suitable for making diagnoses of sleep disorders in older adult populations but can provide information about the risk of having the disorder (Sadeh 2011).

3.1.2   Circadian rhythms parameters from actigraphy

Circadian rhythms from a biological perspective are originated in supprachiasmatic nucleus (SCN) in the hypothalamus. SCN has a rhythm of close to a 24-hour period but it is stimulated and synchronized by various inputs such as light, meals and activity rhythms. It controls and affects peripheral oscillators (heart, lung, liver, intestine and adrenal and adipose tissue) via hormone secretion and the nervous system. Daily light is the most critical mechanism maintaining organismal synchrony with the external environment (the strongest input/zeitgebers).

Circadian rhythm and sleep-wake pattern changes are associated with ageing (Neikrug, Ancoli-Israel 2010, Brown, Schmitt & Eckert 2011). Typically ageing has been considered to increase prevalence of phase advance, distort the circadian rhythm (increased fragmentation), decrease the amplitude and cause internal resynchronization of different rhythms (Brown, Schmitt & Eckert 2011, Garaulet,

Ordovás & Madrid 2010). However, there are indications that, for example, the need for sleep does not change with age (Neikrug, Ancoli-Israel 2010). Illness, degenerated functioning or old age can effect negatively the capability to handle changes in inputs of the circadian system (zeitgebers) leading to disruption of that system (Van Someren, Riemersma-Van Der Lek 2007). For example, people in their eighties receive only 10% of light compared to a 10-year-old child due the changes in physiology (mostly in the eye) (Garaulet, Ordovás & Madrid 2010)

For extracting circadian rhythm parameters from the actigraphy the raw activity values (counts) are analysed. Cosinor analysis was reported to be the most popular method for analysing the rhythm (amplitude, mesor and acrophase, Fig. 5) (Ancoli-Israel et al. 2003). In five parametric cosinor analyses, alpha (width), beta (steepness) and f-statistics (goodness of fit) are added to traditional cosinor analysis.

An assumed 24-hour rhythm is quantified with an autocorrelation and inter-daily stability measures (high autocorrelation and inter-daily stability indicated robust rhythm)(Ancoli-Israel et al. 2003, Van Someren et al. 1999). Circadian quotient characterizes the strength of the circadian rhythm. The amplitude to mesor ratio provides normalized values from cosinor analysis. Another normalized variable is the relative amplitude. In the calculation of the relative amplitude the most active ten-hours periods and the least-active five-hour-period are utilized. Also, non-normalized ratios have been used in the studies.

Other measures reported to explain circadian rhythms were standard deviation of the sleep onset time, intra-daily variability, different spectral analysis, and waveform modelling (Ancoli-Israel et al. 2003) .

Actigraph was found to be a valid method for estimating bedtime, wake-up time, mid-sleep time and acrophase compared with urinary circadian rhythm measures in young and older adults (Ancoli-Israel et al. 2003). Actigraphy, however, is not necessarily a good estimate of SCN (suprachiasmatic nucleus, i.e. brain region for circadian timing control) output due to the masking of environmental pressure such as social activities, artificial light or other environmental stimuli.

Actigraphy has a potential for identifying naps but it should be noted that it can classify the time spent inactive as sleep as well. Actigraphy can be useful in assessing daytime sleepiness when more standard measures are impractical (such as sleep latency test).

Actigraphy is suggested to be valid for characterizing and monitoring of circadian rhythm pattern, e.g. in the older adult population (both in nursing home and with community dwelling older adults) (Ancoli-Israel et al. 2003). Actigraphy recordings correlated well with measurements of melatonin and of core body rhythms (Morgenthaler et al. 2007, Ancoli-Israel et al. 2003). When timing of the habitual sleep patterns were measured with actigraphy at least seven days longrecordings should be made (Van Someren 2011).

3.1.3   Physical activity patterns from actigraphy

Although detailed physical activity tracking has not been very extensively utilized in the sleep and circadian rhythm literature, actigraphs are able to quantify

different aspects of higher levels of physical activity. For example, cosinor analysis provides estimates on the diurnal activity level (amplitude). Diurnal activity was found, for example, to correlate with the functional capacity among nursing home residents. Another common procedure to estimate the activity status for waist-mounted activity monitors is to set a threshold for the activity count for separating between the different intensity levels such as low, moderate or vigorous. In (Moran, Heled & Gonzalez 2004) it was found that the activity measured from a wrist actigraph had high correlation with oxygen consumption. However, the results depended heavily on the pre-processing mode

The telemetric actigraphy, which is utilized in the thesis, was reported to be more sensitive for low-intensity activities, whereas the traditional actigraphs have better dynamics in high-intensive activities (Lötjönen et al. 2003).

3.1.4 Using the actigraph in free-living conditions

In the home environment there are many additional issues to consider compared to in the laboratory. Individuals in the home, for example, spend hours watching television on a couch, forget to put the actigraph on again after a shower or other such activity, drinks lot of coffee or alcohol before bedtime, etc., meaning that the control might not be very good. Actigraphy was considered to be a good technology for documenting intervention effect (Morgenthaler et al. 2007) and presumably helpful for long-term health monitoring. It was considered, for example, to provide reliable information about change (especially on sleep and circadian rhythm parameters) in cognitive behavioural therapy interventions. When reporting findings with the actigraph device and algorithms, reliability and validity, missing data and artefacts (quality measures) should be states (Sadeh 2011). It should be remembered that the ultimate measure of actigraphy is movement.

3.2 Characteristics of actigraphy monitoring

In this section a literature review from the thesis objectives is presented. The first section concentrates on the actigraph's measurement characteristics and in the second section introduces findings on association between the actigraphic data and physical functioning.

3.2.1 Reliability of actigraphy

Reliability describes how reproducible the measurement or observation is in repeated measures in a single individual. Based on the reliability of a measurement one can make conclusions according to the measurement results when for example evaluating an intervention effect's significance. When studying the reliability of the measurement the most typical evaluation metrics are the typical error and the retest correlation (Hopkins 2000). It was noted that the retest correlation (intra class correlation, ICC) depends on the heterogeneity of the participants which

limits its usability. Thus, this highlights the importance of the typical measurement error as an index for reliability. In a related article (Hopkins 2000) it was suggested that a realistic threshold for detecting a real change in the measurement appears to be about 1.5 to 2.0 times the typical error (Hopkins 2000). The reliability information is valuable for long-term monitoring as well from the change detection and decision making perspective.

What is the ideal recordings length needed to reliably assess habitual or typical physical rest-activity behaviour for older adults? Kang et al. claimed that a point measurement, such as one week, does not often generalize to typical activity behaviour over longer periods [(Kang et al. 2009). However, in special groups one-year monitoring already might contain dramatic changes in habitual behaviour and optimal monitoring length would be important to determine for discovering true changes in these behaviours. Kang et al. found by analysing data of 23 middle-aged subjects that average yearly step count (pedometer) was estimated with data from five consecutive days with an ICC greater than 0.8 and with 14 consecutive days with an ICC greater than 0.9. If the real change can be detected with 1.5 to 2.0 times the typical error, the minimum real step change would be 750 to 1000 steps with 30 days averaged step amount (10%*2.0 or 1.5*5000 steps) if a person's typical daytime activity is 5000 step? In (Kang et al. 2009) the two-week recorded data the typical error was 12% on average.

Hart et al. (Hart et al. 2011) assessed waist-worn accelerometers and pedometers reliability to predict 21 days of different types of activity behaviour and concluded that continued use of seven days of monitoring is needed for an ICC greater than 0.8 for older adults. They also found that light and sedentary behaviour needed longer aggregation for accurate prediction (ICC > 0.8) than moderate activity. However, Hopkins argued that the ICC should be at least 0.9 to keep the error rate acceptable and not 0.8 or 0.7 as commonly used (Hopkins 2000). In the study (Hart et al. 2011) to gain a reliable estimate of yearly steps (ICC of 0.9) 11 days of monitoring was needed. Togo et al. found that a reliable estimate of yearly steps for older adults dependent as well on gender, season and consecutiveness of measuring dates. For example, to gain 80% reliability male subjects needed 28 and females only eight consecutive days for a reliable estimate of yearly step amount. It was stated, based on the day-to-day variability, e.g. between weekends and weekdays, that the smallest unit of measurement to capture individual activity patterns should be one week (Baranowski et al. 2008). They also pointed out that consecutive days are not statistically independent (negative correlation) and randomly included days might be a better solution for behavioural monitoring but do not (necessarily) remove season-to-season variation. According to (Baranowski et al. 2008) ICC might underestimate the true needed number of days. Self-reported physical activity instruments mostly assess a minimum of a week's typical activity behaviour (Ong, Blumenthal 2010, Cress 2006) which is also the observed time frame in health enhancing physical activity recommendations (Nelson et al. 2007).

Van Someren studied test-retest reliability of actigraphy-based sleep and circadian rhythm parameters for insomniac and demented subjects (Van Someren 2007). He found that to achieve an ICC greater than 0.8 one to nine days data

would be needed and for an ICC greater than 0.9 from three to ten days, depending on the parameter; circadian rhythm parameters needed longer measurement periods to stabilize. He suggested that similar improvements are likely with other subject groups when the recording period is varied in addition to demented and insomniac subjects and recommended monitoring until two weeks. Sleep habit survey items (questionnaires) typically query the past two weeks sleeping and waking activities for point assessment (Wolfson et al. 2003). According to Knutson (in (Sadeh 2011)) actigraphic sleep measures tend to have more day-to-day variance than yearly/season variability for adults. This suggests that strong season-to-season variation might not be present for the actigraphy's sleep parameters.

However, as reported by van Someren that some activity patterns can change episodically, especially for certain user groups such as older adults captioning the good weeks and bad weeks instead of days might be relevant (Van Someren 2007), especially for health monitoring. Hence, even longer recordings might be relevant for the special groups with possible health problems. In a related article it was suggested that even three weeks measurements are needed to obtain valid and reliable estimates of weekly (social) rhythms for sleep and activity behaviour (Berger et al. 2008).

The literature suggests that aggregated data from at least 7–14 days would be recommended to caption typical activity-rest behaviour. Some studies suggested that the time period could even be longer. With very long measurements we have to be careful not to filter out some relevant episodes due to averaging. Especially, the variability of the behaviour was reported to be one indication of well-being among older demented subjects (Carvalho-Bos et al. 2007). For monitoring or point measures it is important to know the typical measurement error to discover true changes in the behaviour.

The sources that influence reliability when evaluating typical activity patterns with the actigraphs are biological variation, that is, the subjects themselves in their natural environment, and variability on how the data were collected, processed, or reported due to the differences between the devices and algorithms from the different manufacturers (Baranowski et al. 2008). When utilizing the same manufacturer's devices and settings in the study the device-born errors are negligible.

3.2.2 Feasibility and compliance of actigraphy

Compliance for the monitoring device is an important character in practise (word adherence has been used as a synonym). In one study (Biswas et al. 2009) a wrist-worn accelerometer was used for two weeks for detecting total sleep time and sleep periods. Typically, 20 to 30 percent of the data was found to be missing (15 participants with dementia). When sixty subjects were monitored for nine months with a wrist-worn actigraph, ninety percent of subjects finished the period and 90 percent compliance was accomplished when days including a recording were considered (Howell et al. 2010). An exclusion criterion was more than four hours of missing data per day. They also reported that typically data collection

periods have been less than one week for actigraphic studies. Data cleaning algorithms such as those utilized in the study have to be employed.

Mathie et al. (Mathie et al. 2004) succeeded to collect 88% of intended measurement days with a wearable accelerometer. Six healthy subjects aged 80–86 years participated in the study for a two- to three-month period. The accelerometer was suggested to be a feasible method for collection of the activity behaviour data according to the results in (Davis, Fox 2007).

Missing data of 20 percent or higher can be expected in the long-term monitoring concept according to these studies (Biswas et al. 2009, Howell et al. 2010, Mathie et al. 2004, Davis, Fox 2007). Participation in the study might have increased compliance compared to real-life.

3.3 Actigraphy association with physical functioning of older adults

In this section I have reviewed study results from the scientific literature which report associations between objectively measured rest-activity behaviour and physical functioning for older adults. The studies should have included at least five days of continuous activity monitoring or a very significant number of subjects to be included. The search was also limited to wearable actigraphs (also ankle and waist mount was allowed). The first part focuses on the activity levels and the second part on the sleep patterns and circadian rhythms.

3.3.1.1 Actigraphy activity level association with physical functioning of older adults

Davis et al. monitored community dwelling older adults with a belt-worn actigraph for seven days (N=165, average age = 76 years) (Davis, Fox 2007). In addition, they included 45 young (27-year-old) participants with the same protocol. They stated that surveys do not provide chronological information of the day's activity level, which was of interest in the study. They found the older subjects to be less active during the evening hours; most likely due to different social environment (when comparing older adults with and working age group).They also reported that self-reported daily trips (especially with public transportation, walk or by bike) were associated with a greater number of steps (Davis et al. 2011). The same group evaluated connections between physical functioning tests scores and waist-worn actigraph output (1 week measurement, N=240, average age=78). Number of daily steps, daily mean of activity count and activity intensity (minutes in moderate to vigorous activities) correlated positively (RHO≈0.6 with P<0.01) with the functioning estimate (short physical performance battery, SPPB, average for females=9.2, males=10.1). The sedentary (low activity) behaviour measure was not associated with the functioning score (Trayers et al. 2009).

A prospective study of 75 middle-aged participants with chronic fatigue syndrome wore an actigraph (Manufacturing Technology, Inc., Pensacola, USA, MTI)

for three weeks for two times in two years. The results showed that the level of change in average activity counts correlated with change in self-reported functioning (SF36 subscale for functioning, RHO=0.40, P<0.05, that is improved functioning implied increased activity level). However the change in actigraphy measured activity amount was not correlated with performance test change (six-minute walking test). They concluded that the objective measures (such as actigraph) can be an important indication of change in functioning (Friedberg, Sohl 2009).

In the Nagajono study, 183 older adults measured steps and activity amount (minutes in activities greater than 3 MET, which are based on the four-second accelerometer epochs) over one year with a belt-mounted actigraph. Steps and activity amount were highly, positively correlated. The subjects in the first quartile of the activity amount (low-activity group) differed significantly from the two most active quartiles in physical functioning, mental health, vitality (factors of the SF36) and in overall grade of SF36 (the higher the activity level, the better the functioning). Recruiting, however, tended to bias the healthier older adult population. No direct correlation between objective activity measures and self-reported functioning were reported. They noted that causality of the physical activity with quality of life remains studied in longitudinal studies (Aoyagi et al. 2010).

Eighty-two community dwelling older men (average age=74.1) wore hip-mounted actigraphs for seven days. The group was divided in half according to median daily activity count. Higher activity correlated strongly with better functioning (SPPB, gait speed, stair climb and VO2max, R=0.2-0.5), but only moderately with lower and upper body muscle strength. Muscle strength measures did not differ between the two groups. They concluded that physical activity level is a key factor of functioning and mobility in older men (Morie et al. 2010).

Thirty healthy young adults, 28 healthy and 12 older adults reporting functional limitation wore an accelerometer on their ankle for six days ((Cavanaugh et al. 2007). In addition, two more traditionally reported measures (steps, duration of activity and activity count), two measures quantifying variability and randomness of the minute-to-minute activities were included. No significant differences in measures between healthy and functionally impaired older subjects were found. The result suggested that the activity becomes more predictable (lower entropy) and consists of less-complex activity periods along ageing and impairment.

Fifty-six (26 men) community dwelling older adults wore a thigh-mounted accelerometer for seven days. (Lord et al. 2011). In the introduction the authors noted that scheduling and timing might be important for exercise programmes. Activity and sedentary (passive) behaviour are not just their counterparts and both behaviours might not be very well described in a single measure. They stated that multiple measures are encouraged to be used to describe activity behaviour. Three orthogonal components (according to principal component analysis) were distinguished from seven extracted features from the accelerometer data representing 1) walking/physical behaviour, 2) sedentary and 3) postural transitions. Regression analyses (R> 0.20) to estimate factors 1 and 3 from different subject characteristics (e.g. sex, BMI, cognitive, physical/functional, and activity measures) were performed. There were no correlations between the characteris-

tics and Component 2. The timed up and go test and a fall risk inventory (FESI, 16 questions) were included in the models for components 1 and 3 meaning that measured walking/physical behaviour and postural transition were connected to functioning measures.

Two-hundred and forty community dwelling older adults wore (43% of invited) actigraphs on the hip for seven days (Harris et al. 2009). Average step and activity counts were extracted from the data. Reduced step amount was associated with decreased scores in several health measures including disability (modified Townsend disability score) and general health. Also, higher BMI and waist circumference were associated with lower step counts. Depression score (GDS-15) independently predicted step count. They noted that although pedometers may be adequate for most observational studies these do not provide information on rhythm and timing.

Howell et al. studied how actigraphy was related to functioning and medical events for cardiac patients (including older subjects, N=37, average age =77 years) (Howell et al. 2010).They monitored sixty subjects for nine months with a wrist-worn actigraph. 90% of the subjects finished the period. A maximum of ten hours activity (M10), daily activity count and maximum six-minute intensity (M6min) per day were compared to a six-minute walking test and VO2max. M6min had the strongest correlation between the two functioning measures (six-minute walking test R=0.61, P<0.001, positive). When the subjects were divided to older and younger groups the correlation was even better for the older group (R=0.70). In multivariate analysis lower M6min significantly predicted more reported health events such as deaths, hospitalizations, emergency department visits, intercurrent illnesses and outpatient procedures. Assisted living facility residents wore actigraphs on their wrists for, on average, 9.3 days (N=694, average age 82.2±7.0 years). Total daily activity was positively associated with better global motor function (James et al. 2012).

3.3.1.2 Actigraphy sleep patterns and circadian rhythms association with physical functioning of older adults

Study of Osteoporotic Fractures (SOF, observational study of 10 000 older women) began in 1986 (USA). The clinical visits took place approximately every 2nd year and in total nine visits were planned. The subjects wore a wrist actigraph for three days at minimum (four days and five nights were planned) after the eighth study visit. Study of Osteoporotic fractures in older men (MrOS, observation study of 6000 older men) included a sleep research part involving three to five days of actigraphy measures. In both studies several physical functioning-related estimates were collected.

According to SOF data self-reported difficulty in performing daily activities (problems in more than one daily activity) were associated with lower SE and lower TST. In the analysis the subjects were divided into two groups based on TST and SE (TST smaller or greater than five hours, SE smaller or greater than 70

percent). 477 older women's data were included in the analysis (82.9 years) (Mehra et al. 2008).

Sleep duration (analysis was based on the sleep duration groups) had a u-shaped association with the Physical Activity Scale for Elderly (PASE) for male subjects. Walk for exercise was heavily decreased for female short sleepers (less than five hours). They also suggested that voluntary (no sleep disorder diagnosis) sleep deprivation is associated with weight regulation by increasing BMI and body fat. 3055 older male's and 3052 older female's data were included in the analysis (SOF and MrOS) (Patel et al. 2008). Obesity was reported to be one 'new' risk factor of disabilities, especially severe obesity (Lafortune, Balestat 2007).

Five parameter sigmoidally transformed cosine analysis was utilized for studying the association between circadian rhythm and mortality with SOF data (Tranah et al. 2010). Higher amplitude and mesor, and later acrophase indicated decreased functioning according to the ADL questionnaire score. Circadian rhythm parameters had an association with mortality. This connection was independent from physical activity and sleep measures. The questionnaire data suggested that two reasons behind the found risk could be either related to the harmful effect of altered circadian rhythm on metabolics, or it may be a biomarker of advanced physiological ageing and thus be an independent risk marker. The typical phase change in older people (advanced) may be related to ageing of other rhythmic components of the body (peripheral oscillators) than SCN. They also suggested that a more robust living rhythm would then be more beneficial for older adults. 3027 community dwelling older women's data were included in the analysis (average age 84).

A hypothesis in a related article (Goldman et al. 2007) was that "older women with short or long night-time sleep duration, more disrupted sleep, and more daytime sleep would have poorer neuromuscular performance and more functional limitations. Actigraphy, gait speed (six meters walk test), time of five chair stands, grip strength, ADL questionnaire and some typical confounders were included in the analysis. TST tends to have a u-shaped relationship with gait speed, chair stand time and functional limitations. WASO and daytime sleep had a linear association with the same measures than TST and in addition with grip strength. Women who slept ≥1 hour during the day had higher odds of a functional limitation than those with <0.5 hours of daytime sleep. The correlates between the sleep variables and hand grip strength were low and the authors concluded that they did not exist in the data in practise. The results hold up after adjusting for multiple confounders. They suggested that longitudinal studies are needed to find out whether the poor sleep patterns can lead to functioning impairments. Data of 2889 older women were included (SOF data).

In another analysis with SOF data (Stone et al. 2008) found an association with TST similar to a previous article (Goldman et al. 2007) with slightly different categories emphasizing now the extreme values. The analysis also suggested that a functioning limitation may partly explain the reported association between TST and fall accidents. They interestingly pointed out that "our group recently found that daily napping..." (self-reported) "... was associated with risk of falls, whereas

night-time sleep duration was not related to risk of falls". However, the present study findings demonstrated strong associations of actigraphic estimated short sleep and risk of falls, but no relationship of objectively measured napping and risk of falls. Data of 2978 older women were included.

In a study comparing community dwelling older people (N=52) and nursing home residents without dementia (N=122) data were recorded for 14 days (Meadows et al. 2010). Institutionalized subjects had higher daily activity fragmentation (IV), lower mean activity and lower relative amplitude even after controlled for individual factors. No difference between the groups was found in stability between the days (IS). However, level of independency was found to be a significant factor in the model for estimating inter-daily stability (IS) and mean daily activity. They concluded that institution might have an impact on factors which influence the sleep/wake cycle and thus should be considered when planning the daily rhythm of the facility. They encouraged that longitudinal studies are needed that measure rest-wake patterns before and after entering an institutional care facility.

Oosterman et al. recruited (Oosterman et al. 2009)144 community dwelling older people to wore a actigraph on their wrist for seven days. They found that especially a higher index of daily activity fragmentation (IV) was connected to lower cognitive function. Stability (IS) was not connected to cognitive function. Also, the difference between the least active five-hour period and the most active ten-hour period had significant association with cognitive function. This supports the biopsychophysical perspective of functioning, meaning that cognitive functioning was statistically correlated with physical activity measures as well.

Actigraphic sleep pattern associations with self-reported functioning (ADL and IADL) for 121 (average age = 85.3 years) assisted living facility residents with a follow-up measured at three- and six-month periods were studied in (Martin et al. 2010). They stated that assisted living facility residents are at a vulnerable period for further functional decline and for nursing home placement. Baseline ADL was positively associated with TST and SE. Higher SE also predicted worse ADL in three- and six-month follow-ups. A similar effect was not found for IADL. In addition, the number of awakenings was associated with the baseline and the two follow-up measures of depression. They suggested that improving sleep could further delay the care needs in this population.

Wake after sleep onset and sleep efficiency were systematically associated with physical functional measures for 207 community dwelling older adults (average age = 83.5 years). Better sleep efficiency and less wake up time after sleep onset were sign of better functioning status (Kim et al. 2015).

In study by Mormont et al. (Mormont et al. 2000) 192 (age 58 years) colorectal cancer patients wore on their wrists for three days. 24h autocorrelation and I<O index (quantifying percentage of activity during in-bed time, which is above the out of bed time median activity) were calculated from the data. They found a significant linear correlation between the QLQ-C30 -based functioning with the actigraphy autocorrelation (RHO=0.23, P < 0.01) and with I<O (RHO=0.43, P<0,001), but not with mean activity count (that is, the higher self-rhythm correlation and activity

during bed time, the better the functioning). The two measures were also important factors in multivariate models of patients' survival.

In (Lim et al. 2011) a probabilistic state transition model for quantifying the fragmentation of human rest-activity patterns was developed for actigraphic data. They suggested that regulation of rest-activity patterns at smaller scales might be controlled by different neural networks (in the brain) than those regulating such patterns at larger time scales. PSG has been widely studied by temporal organizations for sleep but actigraphy has not, and the state transition model has not been utilized to describe the dynamics of the actigraphic data. Eleven-day actigraphy data from 621 older adults (average age of 82 years) were utilized in the analysis. Activity epochs (every 15 seconds) were classified as rest or activity. Estimates, kRA and kAR (probabilities of rest-activity or activity-rest transitions times; kRA measures fragmentation of the rest periods and kAR fragmentation of activity periods), were calculated from the data. They studied associations between the two measures and daily activity count, M10-L5, inter-daily stability, intra-daily variability and detrended fluctuation analysis. kRA was not strongly correlated with other measures suggesting that it describes a new character of activity rhythms. They reported that decreased sleep efficiency associated with ageing might be related to maintaining sleep rather than initiation of it. kAR was more correlated with diseases and illness risk rather than with age (more fragmented the activity patterns higher the risk of diseases), whereas kRA was more associated with age and gender. With the same material in another study they found that these rest and activity fragmentation indices were correlated with cognitive deficits (higher fragmentation indicated lower function) and could be clinically relevant signs of cognitive decline (Lim et al. 2012).

Carvalho-Bos et al. studied (Carvalho-Bos et al. 2007) association between actigraphic parameters and functioning domains for 87 demented assisted care facility residents (average age 85.5 years). Two dichotomy indices, "wake-active index" (% greater than median activity count of in bed time when out of bed) and "sleep active index", (% less than median activity count of out-of-bed data when in bed), three non-parametric variables (IV, IS and RA), and ratios between L5/M10 and between median when in bed and out-of-bed (Sp50/Wa50) were extracted from two weeks of actigraphy recordings. Rest-activity rhythm ratio and daytime activity variables correlated with physical functioning measures (R=0.25-0.50). In stepwise regression analysis daytime median activity and L5 remained in the model for functional impairment (FAST) and only median activity for ADL measure. IS was the only actigraphy parameter in the regression models for estimating MMSE and mood disturbance score (higher fragmentation indicated worse results).

Four community dwelling and 17 institutionalized demented persons participated in bright light therapy. The sensitivity of actigraphic parameters to detect the treatment was evaluated (calculated over five days). The parameters included in the analysis were: single cosinor and cosinor including second harmonic, complex demodulation, normalized power of 24h frequency in the Lomb-Scargle periodogram, 24-hour autocorrelation, IS, IV and RA. They concluded that IS, IV and 24-

hour autocorrelation are sensitive indices for discovering disturbances in the rest-activity rhythm. IS and 24-hour autocorrelation were sensitive in detecting the treatment effect in the studies (IV decreased, IS and autocorrelation increased due to the therapy) (Van Someren et al. 1999).

In the study, 10 healthy older males took part in long-term fitness training (three months) IV was the only parameter which was significantly improved due to the intervention (0.74 to 0.56 on average). The actigraphy was worn 5½ days on average (Van Someren et al. 1997).

In (Martin et al. 2006) five parametric model of cosinor analysis was utilized for three-day actigraphic recordings of 118 nursing home residents who had sleep disturbances (less than 80% of sleep while in bed). Subjects with stronger circadian rhythm (better fit, F) had less daytime sleep (annotated/observed), higher physical activity level and more social participation. Acrophase or circadian strength were not associated with functioning measures (e.g. MMSE and MOSES). More bright light exposure was associated with a later circadian phase.

Sixty-five healthy volunteers took part in the study to find out age differences in typical actigraphic parameters (Huang et al. 2002). The volunteers were divided to young (N=18), middle-aged (15), old (20) and oldest groups (12). The actigraphy recordings were between five and seven days. The old and oldest group had more fragmented activity patterns (higher IV), more activity during the night (higher L5, SE and fragment index), and lower relative amplitude (RA) compared to the other two groups. IS did not differ between the groups. Age was associated, for example, with a dip in activity during the day (suggested due to naps) and higher night-time activity. They actually (by Monk in (Huang et al. 2002)) suggested that a more stable rhythm (IS) in healthy old subjects could be a response to ageing. In the study the young group lived at a university in a very controlled environment with lights on and off at regulated times, which might have increased their IS.

In (Paavilainen et al. 2005) 42 subjects' data were included in the analysis for comparing the demented (N=23, 84 years) and non-demented (82 years) nursing home residents. Actigraphy data were collected for at least nine days. Mean and median night activity, and night/day activity ratio were higher, and mean daytime activity was lower for demented persons. Poincare parameters quantifying repeatability of the activity as well differed between the groups. They also found that night/day activity ratio was a sensitive parameter for detecting nursing home residents' health status changes (Paavilainen, Korhonen & Partinen 2005).

Song et al. studied actigraphic sleep parameters' associations with physical functioning (ADL and IADL) for community-dwelling older adults in a veteran's day health care programme. Fifty subjects wore an actigraph on their wrist for a minimum of three consecutive days (average age 77.4±9.8 years). Worse functioning according to a combined ADL and IADL score was associated with more night-time awakenings and more daytime sleeping. Longer total sleep time had a correlation with more ADL limitations. However self-reported sleep characteristics (PSQI) were not related with ADL or IADL (Song et al. 2015).

In a study of 97 hypertensive older adults (average age 74.8±3.3 years) physical functioning assessments and actigraph sleep indices were compared. Short

total sleep time (< 7.0 h) and more night-time awakenings (> 2.0 awakenings/ night) led to higher odds of functional limitations ($p < 0.05$) (Reyes et al. 2013).

IV (more fragmented) and IS (less stable) was found to predict all causes of mortality in a large follow-up study of older adults in Rotterdam (N=1734, average age 62.2 ± 9.3 years). However, actigraphy-measured sleep characteristics were not associated with mortality risk when controlled with other health parameters (Zuurbier et al. 2015).

3.3.2 Sleep, circadian rhythms and physical functioning of older adults according to non-actigraphic literature

In the initial part of this section we reviewed literature issuing associations between actigraphic parameters and functioning for older adults, which was the delimited topic of the thesis. However I have tried to give a very short introduction to the topic outside the actigraphy-based literature by very briefly introducing four theoretical or review articles to describe how ageing, health and function, can be related with sleep and circadian rhythms.

Van Someren discussed in a theoretical review the kinds of effects different zeitgebers might have on circadian rhythm and health. Zeitgebers are environmental inputs (queues) which stimulate the human circadian clock system. The most typical zeitgebers are light, body temperature, melatonin, physical activity and meals. Van Someren used a swinging child as a metaphor to illustrate how illness and ageing might influence an older person's ability to respond to the different zeitgebers and their disruptions. The hypothesis is that irregular or lack of zeitgebers can only be compensated with a strong endogenous oscillator, and weak endogenous timing system needs strong and regular stimuli (corresponds to pushing aid in the swinging metaphor). A key message was that ageing and especially ill health in old age can highlight the negative consequences of zeitgeber disruptions. In the swinging metaphor these persons do not master the correct leg extension. The author suggested that compensation of a vulnerable circadian clock system might be visible among older adults in a very stable lifestyle (unconscious adaptive response) and that regular zeitgebers can be an effective intervention on older people's wellbeing and care. On the other hand, reactions to different zeitgebers can provide information about the health status of an older person (Van Someren 2007).

A short review on sleep disorders in older adults was presented in (Neikrug, Ancoli-Israel 2010). It was reported that sleep disturbances in old age are more of a function of other factors than age itself. Older people with poor sleep have a risk for decreased physical functioning, memory problems, increased fall risk and mortality. As people age, their circadian rhythms become weaker, desynchronized and lose amplitude. This emphasizes the role of external cues (such as bright light) for maintaining a good sleep-wake cycle. One factor contributing as well to the sleep-wake cycle is melatonin, the secretion of which gradually decreases with age (Fig. 4) and thus represents one potential source of concern. Also, the phase advance is common in older patients meaning that they wake up earlier and get

tired earlier. The authors though noted that staying up late might not help since they still wake up early and might get less total sleep due to this.

The three most common primary sleep disorders among older adults are sleep disordered breathing (e.g. sleep apnea), REM sleep-behaviour disorder and restless leg syndrome/periodic limb movement.
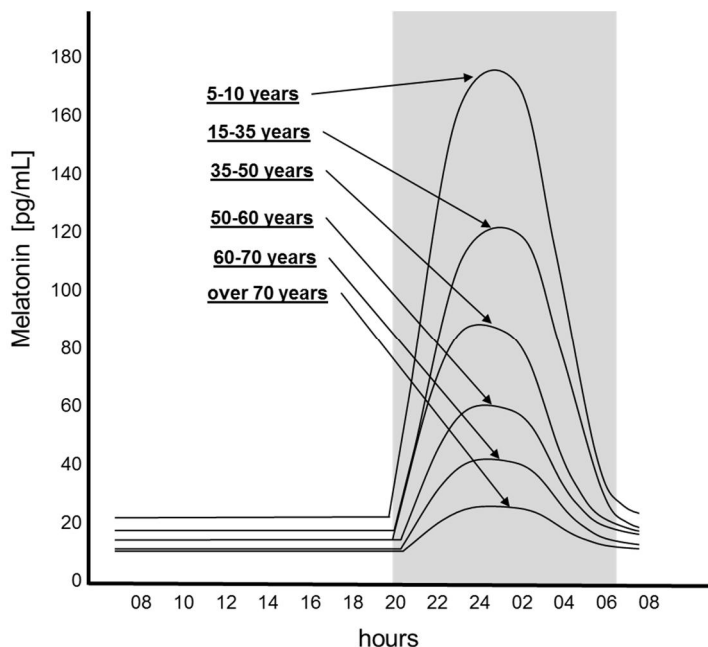

Figure 4: Melatonin secretion estimate during the circadian cycle for different age groups (adopted from (Karasek, Winczyk 2006). .

In a research perspective paper, Brown intended to discover possible reasons behind the fragmented sleep and early waking up time in old age. Brown's hypothesis is partly based on the model in which two separate processes regulate sleep: circadian (humans preferably sleep at night, CSN regulated) and homeostatic (sleep drive increases with a function of time spent awake). According to studies the circadian amplitude damping, which is typically associated with ageing, can cause fragmented sleep and increase the daytime napping need. In addition, the documented reduction in homeostatic sleep drive due to ageing can cause a similar effect. Also hormonal changes due to ageing were proposed as a source of altered sleep/wake rhythm. However no hard evidence exists revealing the real model causing disrupted sleep in old age (Brown, Schmitt & Eckert 2011).

A clinical review of daytime sleep associations with functioning found that the reasons behind naps are multiple ranging from socio-cultural to sleep deprivation. However, only a small amount of research there exist how the naps are effecting

on general functioning of individual. Prevalence of napping among older people is higher than in younger adults. Changes in night-time sleep, circadian rhythms, comorbidies and lifestyle factors typically effect the napping habit. Nap amount as well increases with age. The authors claimed that a loop may be formed between night-time sleep and naps, as naps might disturb night-time sleep and vice versa. However good and poor sleepers did not report a different amount of naps on the group level. Especially among cognitively impaired elderly, naps have been associated with morbidity and mortality. They concluded that naps are associated with health rather than bad sleep. To some extent older adults with poorer health might even benefit from brief, planned naps. However frequent unplanned naps might indicate health problems (Ficca et al. 2010).

3.4   Summary of the related research

In the literature various methods existed for extracting actigraphic variables which have been compared to different functioning status estimates in the older adult population. Most typically reported connections with sleep patterns were u-shape correlations between functioning and total sleep time, and a linear connection between sleep efficiency and disabilities (the better the sleep efficiency, the better the functioning state. Activity levels were widely associated with physical functioning although in some articles especially indices for describing sedentary (passive) behaviour were not associated with functioning. Measures describing circadian rhythm fragmentation, stability and strength were also commonly reported. Especially, the fragmentation indices tend to have connections with functioning status. Nonparametric methods for quantifying stability (IS) and fragmentation (IV) were well represented and studied measures in the literature. Utilization of widely reported indices in the analysis makes it possible to compare the new findings and methods with other relevant studies.

Aging and wellbeing has effects on sleep, activity and circadian rhythms according to clinical and theoretical publications. Older adults were more prone to develop ultradian and fragmented activity rhythms. Qualities of the environmental stimuli, such as light, feeding, physical and social activities, contributes to circadian rhythm maintenance. For example, stable lifestyle and stable zeitgebers have been shown to be present and support healthy ageing, whereas irregular or other negative stimuli have more harmful effects on aged persons and those of ill-health.

Sleep disturbances in old age were associated more with health than ageing itself although, for example, phase advance is typical for older adults. Also dampening of the circadian rhythm amplitude might fragment sleep and lead to increased daytime sleep (napping). However napping is also cultural and probably individual dependent, emphasizing the need for including personal historic data in monitoring. Involuntary naps can contribute to a loop where napping, activity and sleep all affect each other positively or negatively. When considering naps from an actigraphic perspective we have to remember that passive behaviour might not be well separated from sleep.

4. Summary of publications

This chapter describes the methods and results of the thesis. The recording device, collected material and analysis methods are presented. The results section summarizes Studies I–VI and presents relevant new results based on the collected material.

4.1   Device

The device used to collect data for the studies, called a telemetric actigraph, is a social alarm system (i.e. wrist-worn panic button device, Vivago Inc., www.vivago.fi, Helsinki, Finland) with an integrated activity sensor. Typically the wearer of a social alarm unit calls for help by pressing the button on the device and the call is directed to a selected receiver, such as the phone of a nurse. In addition to this the telemetric actigraph system can raise an alarm by analysing changes in the recorded subject's activity data (Sarela et al. 2003).The telemetric actigraphy system consists of three parts; a wrist unit, a base station, and alarm receiving and routing software in a server computer (Fig. 5). The wrist unit has a manual alarm button and sensor technology for activity and adherence/compliance monitoring. Compliance is monitored by detecting whether the device is on a wrist or not. The adherence monitoring is based on the skin conductivity measurement (Sarela et al. 2003). For example, if a device is removed from the wrist and not put back the system will be informed of this. Activity is detected by sensing the force differences between the device and wrist. The activity values are sent to the backend system via the base station. If the wrist unit is taken outside the base station range the activity data is not stored in the backend system. The connection between the base station and the wrist unit is absent if the distance between them in an open area is more than 100 metres or obstacles exist between them preventing the radio signal transmission. The missing data point is marked in the server's data collection as an 'out of range' value.

Dataset 1 and Dataset 2 were collected with a device version named Wristcare (Studies I–IV, VI) and Dataset 3 was collected with a device version named PWM1 (Personal wellness manager, Studies V). Strap type and activity sensor positioning differ between the versions, which can cause some changes in the activity signal values. No published data exist comparing the actigraph data of the two devices.

Figure 5: The telemetric actigraph system: WristCare wrist unit, PWM1 wrist unit, base station and server software.

The back-end system (receiving and routing software) collects automatically minute-to-minute wrist activity values sent by the wrist unit. The system performs minute-to-minute sleep/wake classification with a similar accuracy to actigraphy, which is the most used alternative to the polysomnography in sleep analysis (Lötjönen et al. 2003). The agreement with the PSG was 77% for the telemetric actigraph and 75–77% for traditional actigraphy among older people (Lötjönen et al. 2003). Both modalities overestimated the total sleep time similarly, around 1 hour a night on average, for the older subjects.

The telemetric actigraphy is reported to be more sensitive to low-intensity activities, whereas the traditional actigraphs have better dynamics in high-intensive activities (Lötjönen et al. 2003). The modality is sensitive for detecting micro and macro movement of the wrist. For example, knitting and similar activities are captured. The traditional actigraph and the telemetric actigraph activity counts had moderate correlation (Pearson R=0.52) (Lötjönen et al. 2003). This difference has to be considered and validation is needed if processing methods targeted for absolute values of actigraphy's activity count are utilized in the analysis with the present (Vivago) telemetric actigraph data.

The telemetric actigraph monitoring was found to be a sensitive method of detecting changes in the health status of older adults, especially when it was compared to the users' own history data (Paavilainen, Korhonen & Partinen 2005). It was also concluded that the most promising aspects of the device are its unobtrusiveness and high compliance due to the alarm features; both manual and automated (Paavilainen, Korhonen & Partinen 2005). The automated, adaptive alarms help to call for help if the wearer cannot activate the alarm themselves, for example, due fainting or a seizure leading to long immobility.

The device's minute-to-minute activity signal's deviation was found to differ between light and deep sleep (Lamminmäki et al. 2005). The authors concluded that although the exact sleep stage classification is not possible, the signal could provide valuable information on sleep duration and quality.

4.2 Datasets of the studies

There are four datasets utilized in the thesis analysis. Table 1 summarizes the subjects' demographics and functioning status estimates in the datasets. The datasets and instruments utilized in the studies are presented in more detail in the following sections.

Table 1: Descriptive information of the subjects in the datasets. MMSE = minimental state examination, GDS= Geriatric depressions scale, CPS = Cognitive Performance Scale, ADL = Activities of Daily Living, DRS = Depression scale

Dataset Variable	Dataset 1 without dementia	Dataset 1 with de- mentia	Dataset 2	Dataset 3	Dataset 4 older subjects
Number of Subjects	19	16	17	23	15
Age [years ± SD]	81.5 ± 9.0	84.3 ± 9.5	78.2 ± 8.2	90.9 (4.7)	78 (7)
MMSE score	26.2 ± 2.9	11.6 ± 5.6	27.3 ± 3.7	19.4 (7.8)	-
RAI DRS				1.8 (2.5)	-
GDS-15 score			1.9± 1.6	5.4 (3.4)	-
GDS-5 score	0.4 ± 0.7	1.0 ± 1.1			-
ADL questionnaire score	32.5 ± 9.1	40.5 ± 4.9	21.7 ± 7.6		-
RAI ADL				1.4 (1.8)	-
Males/females	2/17	2/14	6/11	1/ 22	-
Study	VI	VI	I-IV, VI	V	(in thesis) unpublished data

4.2.1 Dataset 1 (Study VI)

The primary objective for collection of Dataset 1 was to study how the telemetric actigraph data differ between demented and non-demented nursing home residents, and how it correlates between subjective assessment of sleep and alertness. The subjects were from two nursing homes and the selection of the institutes was based on the prior use of the system. Written consent was received from the subjects or from their relatives in cases of severe dementia. The exclusion criterion for the study was a chronic condition seriously affecting wrist activity, such as Parkinson disease. The study was approved by an appropriate ethics committee. Forty-two subjects volunteered for the study (23 demented, when

dementia criterion was MMSE <=20 and CDR >=0.5). Table 1 presents the demographics of the subjects. Results and analysis on the primary objectives are presented in the related research (Paavilainen et al. 2005, Paavilainen, Korhonen & Partinen 2005). For Institution I the data were collected for 10 days and for Institution II for 113 days. In addition to the actigraphic data, the following measures were collected in the beginning of the study (Table 1):

- Clinical Dementia Rating scale (CDR): 0,0.5,1,2,3 (0 for no impairments, 3 for sever impairments)
- Mini-mental State examination (MMSE): 0 to 30 (30 for no memory problems)
- Five-Item Geriatric depression scale (GDS-5): 0 to 5 (2 or greater for further evaluation)
- Basic and instrumental activities of daily living questionnaire (ADL): The ADL questionnaire included 14 items on a four-point scale and it has been utilized in large population studies (Heikkinen, Waters & Brzezinski 1983). A subject or a processional estimates of the difficulty in performing an activity (without difficulty=1 / with difficulty, but without help=2 / only with help=3 / not able to perform=4). The evaluated activities were move outdoors, walk between rooms, use stairs, walk at least 400 metres, carry a heavy object, use the toilet, wash themselves, dress and undress, get in and out of bed, prepare food, feed themselves, cut their toenails, do light housework, and do heavy housework. The sums of all the components' scores were used to describe the functioning status of a subject in the analysis 14 to 56 (14 for no impairments). Similar questionnaires are reported to have 0.85–1.0 inter-rater reliability and 0.8–0.99 test-retest correlations (National TOIMIA network). The ADL questionnaire has very similar content with the widely used Katz Index and Brody scale. Experienced researchers collected the data using face-to-face interviews.

The following sleep-related self-reports and observation were collected during the study:

- Sleep log: bedtime, awake time, and number of nocturnal awakenings
- Quality of sleep on a scale from one to five

4.2.2 Dataset 2 (Studies I–IV, VI)

The subjects of Dataset 2 were older people who lived in assisted living facilities which provided accommodation and rehabilitation services (Table 1 and Table 2). The telemetric actigraphy was part of the study equipment. The inclusion criteria were having self-reported sleep problems, loneliness or low physical activity. The exclusion criteria were having an acute disease, being in the active degeneration phase of a chronic disease, having a known disturbing event like a surgery during the study. Some of the subjects took part in the intervention to improve their physical activity. The intervention is described in more detail in Study II. The study included a baseline measurement period of two weeks before the intervention.

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During the study the following health and physical functioning data were collected with questionnaires and performance tests. The results are presented in Table 2.

- MMSE
- ADL (same as in Dataset 1)
- 15-item Geriatric depression scale (GDS–15); 0 (no depression) to 15 (15 for extreme depression)
- Sleeping pill usage; <yes, no>; mainly for controlling sleep and circadian (diurnal) rhythm-related features in the analysis

Performance test (based on the Finnish TOIMIVA instrument, reference values are given in (Finnish State Treasure))

- Hand grip test of both hands (**Hand grip**); results depends on gender
- Time for five chair rises (**Chair rises**); age and gender do not have major effect on the result
- Crouch times (**Crouches**): crouching as many times one can (max 50 times); depends on gender, but good reference values for older people are missing
- Walking speed for 10 metres (**Walk test**); age and gender do not have a major effect on the results
- **Balance** test; standing with feet together, retrieving object from floor, turning 360 degrees, tandem stance, standing on one foot – derived from Berg Balance Scale, (scale 0–20; worst-best). Age and gender do not have a major effect on the results

In addition to older subjects, Studies I and II included middle-aged subjects from a stress rehabilitation programme. The middle-aged data is described in details in Study II. The analyses in the thesis do not include the middle-aged data.

Table 2: Result scores of the performance tests in Dataset 2.

Variable: average± standard deviation	Older subjects (N=19)
Hand grip (right/left)	22.3 ± 8.9 /22.4±7.8
Chair rises [sec]	11.3 ±3.1
Crouches	27.9 ± 16.0
Walk test [sec]	8.4 ±1.9
Balance	15.2 ±3.3

4.2.3   Dataset 3 (Study V)

The Dataset 3 was collected from a nursing home in which the telemetric actigraphy system is in daily use with most of the residents. Sixteen subjects' data were included in the analysis in Study V (Table 1). In addition to telemetric actigraphy, the Resident Assessment Instrument (RAI) is collected in the facility every six months. RAI is a widely used instrument in the nursing home setting globally.

The results of the instrument are used for assessing care and resource needs in the facility. Four indices describing functional capacity of the residents were included in the analysis from RAI in Study V.

- Physical Functioning (Disabilities): Activities of the Daily Living (ADL) scale ranged from zero (no impairment) to six (total dependence). Higher-level activity disabilities such as dressing were assigned with a lower score, whereas loss in basic activity such as eating gained a higher score. The instruments assessment focuses on resident's personal hygiene, toileting, locomotion and eating.
- Cognitive Functioning: "The cognitive performance scale (CPS) combines information on memory impairment, level of consciousness, and executive function, with scores ranging from zero (intact) to six (very severe impairment). The CPS has been shown to be highly correlated with the Mini Mental State Examination, which is very commonly utilized instrument in these settings" (On average 2.0 with 2.5 standard deviation).
- Pain: The scale ranged from zero (no pain) to three (daily severe pain) and has been shown to be strongly connected to the visual analogue scale-based pain measure (on average 0.9 with 0.9 standard deviation).
- Mental Functioning: A seven-item depression scale (DRS). The score ranged between zero (no mood symptoms) and 14 (all mood symptoms during the last three days). Background information from health records (e.g., age, gender, diagnosis, and medication) was included in the analysis (on average 1.8 with 2.5 standard deviation).

In addition MMSE and GDS-15 were collected in the beginning of the study.

4.2.4   Dataset 4

Dataset 4 consisted of data from related research (Lötjönen et al. 2003). In the study the telemetric actigraphy's sleep-wake classification was validated and reported. The collected material included simultaneously registered telemetric actigraphy data and traditional actigraphy data ((ActiWatch, Cambridge Neurotechnology, AW4). The recordings were at least three consecutive days and nights long (average 4.2 days, sd 0.7) (Lötjönen et al. 2003). Fifteen older people (average age 78 SD 7 years) and 13 middle-aged (44 SD 10 years) subjects were included in the study. The older subjects were recruited from the day centres and represent quite well the telemetric actigraphy's user profile. The devices were placed on the non-dominant wrist of a subject. Most of the middle-aged subjects did not wear the telemetric actigraphy during the day, whereas all the older subjects did. The traditional actigraphy file was transformed to one-minute epochs (Lötjönen et al. 2003). Data from the subjects physical functioning was not collected. The older subjects lived independently at home.

4.3   Actigraphy data analysis procedures

In Chapter 2 it was presented that actigraphy can be used to infer a wearer's activity levels, circadian rhythm parameters, and sleep/wake patterns. The most typical processing methods for quantifying these three measures encountered in related literature were selected for the analysis. This section describes these data processing methods. In addition to the selected methodologies, new parameters to evaluate the stimulus-response relationship have been developed and presented. The methodologies are presented in Studies I, III–VI. Table 4 presents a summary of utilized parameters/procedures.

Table 3: Actigraphy processing methods included in Studies II–VI.

Parameters	Study / Abbreviation	III	IV	V	VI
Dataset(s)		2	2	3	1,2
Daytime sleep/passive amount [minutes]	NAP (+ SD)	x (x)	x	x	x
Average daytime activity level [epoch]	DAY ACT		x		
Circadian rhythm strength	CRS		x	x	x
Wrist unit have no connection to base station	Out of range		x		x
Night-time standard deviation of the acti-graph	NIGHT ACT		x	x	x
Total sleep time [minutes]	TST		x	x	x
Sleep efficience	SE				x
Cosinor mesor	MESOR			x	x
Cosinor amplitude	AMPL			x	x
Cosinor acrophase	PHASE			x	x
Inter-daily stability	IS			x	x
Intra-daily variability	IV			x	x
Relative amplitude	RA			x	x
Number of awakenings	AWEKN			x	x
24-hour autocorrelation	ACORR				x
Housing rhythm correla-tion	HOUSE				x

4.3.1 Day- and night-time activity levels from actigraphy

The daytime average activity count (DAY ACT) is considered to tell about the total activity level of a day. The measure was introduced in a related article (Paavilainen et al. 2005). DAY ACT is the average of absolute epoch values between 9 AM and 9 PM.

Night-time standard deviation of the activity epochs (NIGHT ACT) was found to differ between the sleep stages (Lamminmäki et al. 2005) and is considered to provide information about sleep quality/restlessness in the analysis. Smaller values are considered to imply more deep sleep.

The time periods the wrist unit is outside the base station range are stored in the system as described in Section 4.1. We created a parameter which is a daily duration of the device being away from the base station range (see Study IV) named "Out of range". For example, for active persons (i.e. spending lot of time outside home and the facility) a significant amount of activity data can be missing during the daytime. In this case the value for "Out of range" is high.

4.3.2 Circadian rhythm parameters from actigraphy

4.3.2.1 Cosinor analysis

In the cosinor analysis a cosine curve is fitted on the actigraph signal by adjusting the cosinor formula's parameters. The fitting is based on the least squares method utilizing trigonometry. From the cosinor analysis amplitude (AMPL), mesor (MESOR) and acrophase (PHASE) were extracted for the analysis in Study V and Study VI (Halberg et al. 1972) (Figure 6). Extended cosinor methods exist which infer more parameters (Martin et al. 2000) or cosine curve transformations, such as the Hill's function or the anti-logistic function (Marler et al. 2006). We have left them out from the current analysis due to the vast amount of methods already included.
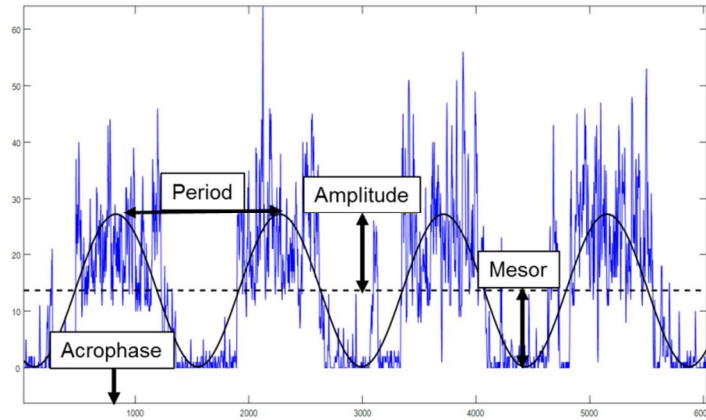
Figure 6: Cosinor analysis parameters. X-axis is minutes from the beginning of the recording. Y-axis presents absolute epoch values of the telemetric actigraph. Blue line is the original actigraphic time series data. Black line is the fitted cosinor data.

The cosinor analysis is performed in the following steps (Cornelissen 2014).

The cosine formula can be written

$$Y(t) = M + A cos(2\pi t/\tau + \varphi) + e(t) \qquad (1)$$

When τ is 24 hours we can write the formula as

$$Y(y) = M + \beta x + \gamma z + e(t) \qquad (2)$$

Where

$$\beta = A cos(\varphi); \gamma = -A sin(\varphi); x = cos\left(\frac{2\pi t}{\tau}\right); z = sin(\frac{2\pi t}{\tau}) \qquad (3)$$

For solving the unknown parameters least squares equation can be written as (Y is now the original actigraphy)

$$RSS = \sum_i [Y_i - (\hat{M} + \hat{\beta} x_i + \hat{\gamma} z_i]^2 \qquad (4)$$

RSS is minimal if the first derivative of each parameter (M, β and γ) is zero. The matrix form of the derivatives can written as

$$\begin{pmatrix} \sum Y_i \\ \sum Y_i x_i \\ \sum Y_i z_i \end{pmatrix} = \begin{pmatrix} N & \sum x_i & \sum z_i \\ \sum x_i & \sum x_i^2 & \sum x_i z_i \\ \sum z_i & \sum x_i z_i & \sum z_i^2 \end{pmatrix} \begin{pmatrix} M \\ \beta \\ \gamma \end{pmatrix} \qquad (5)$$

After solving the equation amplitude (A) and acrophase (φ) can be determined as:

$$A = (\beta^2 + \gamma^2)^{1/2} \qquad (6)$$

$$\varphi = arctan\left(-\frac{\gamma}{\beta}\right) + K\pi \qquad (7)$$

where K is an integer and depends on the sign of a acrophase estimate (φ). M is the mean value of the actigraphy signal.

4.3.2.2   Autocorrelation

Because physical activity typically varies close to a 24-hour rhythm, the 24-hour autocorrelation (AUTOCORR) has been used to quantify the systematic of the 24-hour rhythm. The autocorrelation function has been referred to as "memory" of the time series (Taylor 1990). In practise the autocorrelation is calculated with a 1440-minute lag for the telemetric actigraph data. The algorithm is

$$r_k = \frac{\sum_{t-1}^{N-k}(x_t - x)(x_{t+k} - x)}{\sum_{t-1}^{N}(x_t - x)^2} \tag{8}$$

Where x_t = activity value for minute t

k = lag i.e. to how much later the sample is moved (1440 in the analysis is fixed)

x_{t+k} = sample at minute t with lag k

N = number of observations in time series

x = mean of the time-series signal

The divisor makes sure that the autocorrelation with zero lag is scaled to 1.0.

4.3.2.3   Parameters based on the hourly bins

Circadian rhythms parameters' inter-daily stability (IS), intra-daily variability (IV) and relative amplitude (RA), require a minute-to-minute active/passive classification. According to the active/passive classification hour bins are formed by counting the number of active minutes during the hour.

IS describes the stability between the days implying stable zeitgebers. It is the 24-hour value of chi-square periodogram. It is calculated as

$$IS = \frac{n \sum_{h=1}^{p}(x_h - x)^2}{p \sum_{i=1}^{n}(x_i - x)^2} \tag{9}$$

where n = total number of hour bins

p = number of data per day (24 in this case)

x_h = hourly mean over all hour bin (for example between 16:00 and 17:00 for all the days)

x_i = individual hour bin

x = mean of all hour bins

IS varies between zero for Gaussian noise and one for a perfect match between the days, that is, the averaged hour bins and daily hour bins have equal variance. If daily hour bins would differ substantially from each other, the average hourly bin would approach the average of the data and IS would approach zero. The length of the measurement affects slightly the score.

IV quantifies the fragmentation of the rhythm and activity. It is the ratio between the variance of the consecutive hour bins and overall variance.

$$IV = \frac{n \sum_{i=2}^{n}(x_i - x_{i-1})^2}{(n-1) \sum_{i=1}^{n}(x_i - x)^2} \tag{10}$$

IV gets values near zero for a perfect sine wave and about two for Gaussian noise meaning that more fragmented activity data yields larger values. For example, Meadows et al. (Meadows et al. 2010) reported that high IV (>1) was an indication of daytime naps and/or night-time arousals.

From the averaged hour bins the least active five-hour period (L5) and most active ten-hour periods (M10) are extracted. The relative amplitude is calculated as

$$RA = \frac{M10 - L5}{M10 + L5} \qquad (11)$$

In addition, the average M10 and the average L5 were included in the analysis. Figure 7 presents an example of three different activity profiles in hourly bin data including IV, IS and RA values.
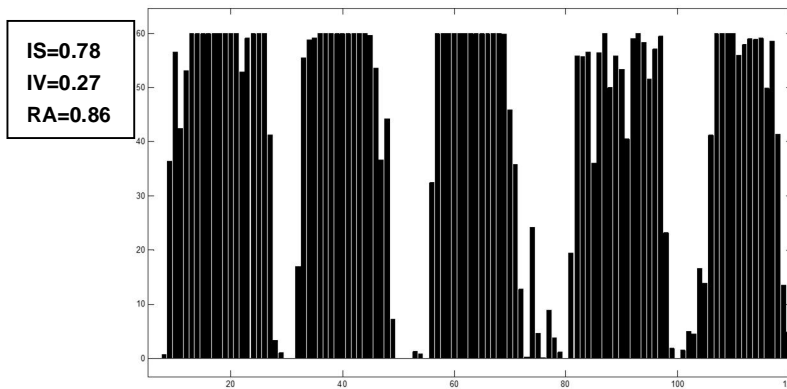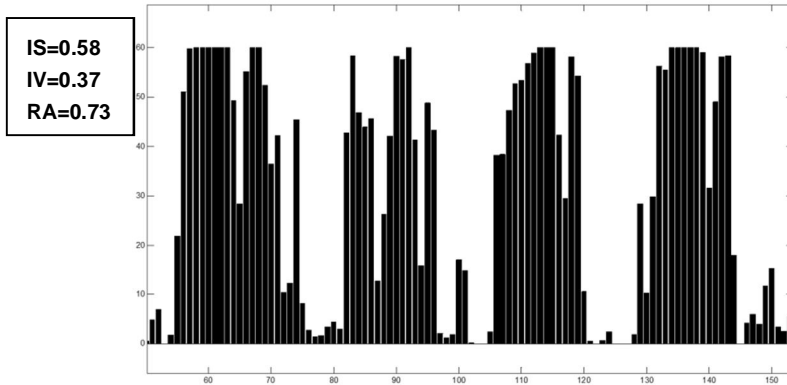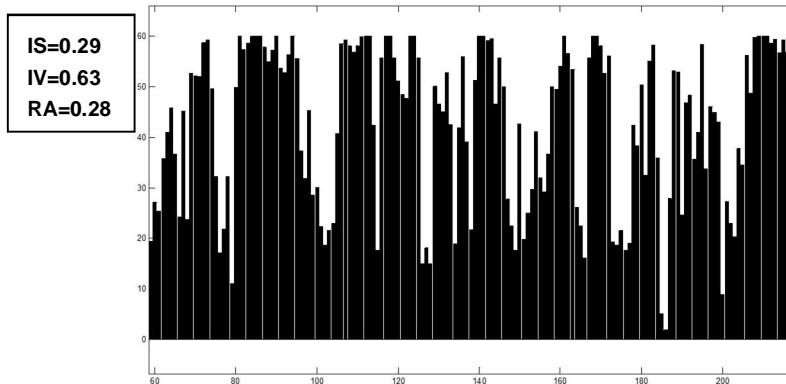
Figure 7: Three examples of hourly bin data with estimates for intra-daily variability (IV), inter-daily stability (IS) and relative amplitude (RA).

4.3.2.4   Circadian rhythm strength

Circadian rhythm strength (CRS) was calculated by dividing average night-time activity (11PM – 5AM) by the average activity of the previous day (8PM – 20AM) for each available circadian(Paavilainen et al. 2005). The average value of the daily CRS score is used in the analysis. CRS is utilized in the telemetric actigraphy system to describe a person's health status.

4.3.3   Sleep patterns from actigraphy

According to the minute-to-minute activity epochs, sleep/wake classification is performed based on the algorithm reported in the related article (Lötjönen et al. 2003). The bedtime information (subjects or nursing personnel annotated) was present for Dataset 2 and partly for Dataset 1. In case the sleep diary was missing the long-term activity data were observed and constant bed times were selected (Study V, Study VI case demonstrations). The constant time points were selected based on the activity profile by observing double-plotted actograms.

Total sleep time (TST) is a sum of sleep classification during in-bedtime. NAP is the sum of sleep classifications during the daytime, between 9 AM and 9 PM. in the analysis. The same daytime period had been utilized in related research (Paavilainen et al. 2005). Awakenings are count of transitions from sleep to wake during the in-bed time. Sleep efficiency is a percentage of sleep during the in-bed time (only used with the sleep diary). The settings for sleep/wake classification procedure for older people with low functional capacity were done according to the manufacturer's recommendations when it was applicable.

4.3.4 Stimulus-response parameters from actigraphy

It has been suggested that the health state, physical functioning and age have an effect on a subject's capabilities of reacting to different environmental stimuli (Van Someren, Riemersma-Van Der Lek 2007) . In addition, environmental factors are suggested to relate to daily activities, participation and body functions in the WHO's model of functioning (WHO 2015). In the thesis we have studied how stimulus-response relation could be utilized for quantifying older adult's physical functioning status. A parameter for quantifying how living facility rhythm reflected on the subjects' activity behaviour was included in Study VI. Association between weather variables and individual activity patterns and how these are affected by the physical functioning level were observed in two case demonstrations in Study VI. These types of analysis have not been previously studied in a similar context.

4.3.4.1 Nursing home activity rhythm as a stimulus

Since the stimulus-response relationship metrics for actigraph data has not been studied earlier almost at all, we studied new processing methods for inferring parameters of the topic. A novel indicator for describing how much a personal activity correlates with an institute's joint activity (named housing correlation (HOUSE)) was created. The indicator was formed with the following procedure:

1) A period close to ADL inquiry (less than two weeks from the inquiry) which included 14 days of actigraph data for the subject of interest and which included actigraph data from other residents without a major interruption was identified (time period selected manually via visual inspection).

2) The actigraph data from each subject were normalized and smoothened from the selected time period (scaled from zero to one and filtered with a 60-minute moving average). This helps to reduce differences between the subjects' mean activity levels and better synchronises the timing of the common activities between the individuals.

3) These normalized actigraph data are averaged for each minute over all the residents (excluding the person of interest). This combined 14-day-long activity data is called a grand average (Fig. 8).

4) From the grand average common, facility-specific active periods are identified by subtracting the mean of the daytime grand average activity for each day and preserving only positive values (the timestamps of the daytime were identified from the grand average for each day individually using ad hoc threshold values; 0.05 or 0.06 was used in practise). This residual data were considered to represent facility activities such as meals or social events (Fig. 8).

5) The Pearson correlation was calculated for each subject, between the individual's actigraph data and the grand average-based facility activities data.
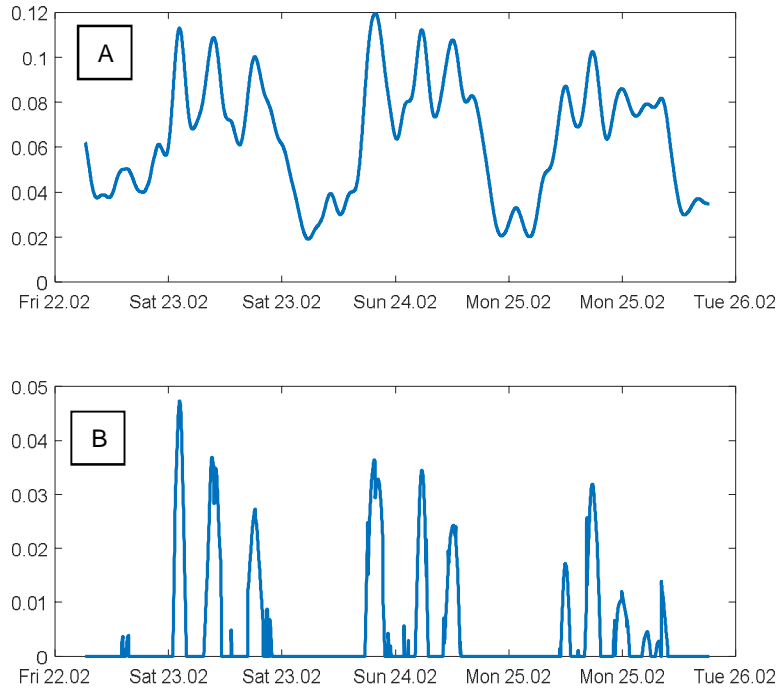
Figure 8: A) Example of the grand average signal over 14 subjects before baseline removal. Threshold of 0.05 was utilized for the daytime detection. B) Three days of grand average data after daily mean level removal, which intends to represent common activities of the facility. Units are normalized and averaged values of the activity epochs. These values do not associate with the original actigraph data well. Time is given on the x-axis.

4.3.4.2 Local weather patterns as stimuli

The Finnish Meteorological Institute has several measurement points in Finland that collect environmental information such as temperature and sunlight radiation. For studying how local weather affected the older subjects' rest-activity behaviour, local daily weather observations on sunlight radiation duration, temperature, barometric pressure and wind were ordered from the meteorological institute. In the case analysis (Study VI) these data were correlated with individual rest-activity behaviour parameters.

4.4 Statistical analysis

The feasibility of the telemetric actigraph monitoring among older adults was evaluated qualitatively via a questionnaire in the study. The compliance of the telemetric actigraph system was evaluated by observing a typical percentage of the device on the wrist during normal use of the system. The telemetric actigraph detects if it is on the wrist or not. Compliance was analysed in Studies II and V.

Validity of the actigraph's physical activity level estimates were analysed with Dataset 2, which includes self-reports on physical exercise and sleep, and daily pedometer recordings in parallel with actigraphy data. Correlations between the methods were reported in Study III. The correlation table in Study III was extended for the thesis to better cover the validity analysis.

Circadian rhythm parameters validity analysis is included in the thesis and it is not published elsewhere. Bases on Dataset 4 the telemetric actigraph and a traditional actigraph are compared (Lötjönen et al. 2003). Pearson correlation and absolute mean error are utilized in the validity analysis.

The test-retest reliability of the different actigraphy parameters were analysed by observing percent standard error between two consecutive recording periods with varying period lengths similar to related research (Van Someren 2007). The analysis is not published elsewhere. The analysis illustrates how much the rest-activity behaviour changes for older adults during daily life in a short period when no health changes are present.

Association between the telemetric actigraphy parameters and physical functioning estimates were analysed with appropriate correlation analysis and by observing the actigraphy parameters' absolute values in different levels of functioning. The results with Dataset 1 and Dataset 2 describe findings mostly on the group level (Studies III, IV and VI). With Dataset 3 sensitivity of the parameters to detect changes in the functioning status was analysed on group and individual levels (Study V). We considered findings significant if the probability of the analysis was below 0.05 and interesting if the value was below 0.1 since the number of subjects in the analysis was moderate. We utilized Bonferroni correction for multiple comparisons in Studies V and VI.

4.5 Results

4.5.1 Compliance and user feedback

Results on the comfortability of the device were analysed in Study II. The main finding was that the wrist unit of the telemetric actigraphy felt somewhat uncomfortable. However there were still fewer negative replies than positive. 44% of older adults gave positive feedback and 38% gave negative. Another finding was that older adult users felt that daily health measuring was more natural and less cumbersome than working age users from a stress rehabilitation programme.

We evaluated the compliance by reporting a typical percent of the device on the wrist during normal use of the system. The periods when the device was taken off of the wrist or when it was not sending the activity data to the base station for other reasons (for example when a battery was replaced or the device was broken) were considered non-compliant time. The detection of whether the device is on the wrist is based on skin conductivity measurement. Periods when a wrist unit was outside the base station range (see 4.1 for more details) (Sarela et al. 2003) was considered as compliant. The compliance was analysed in Study II and in Study V but are reported systematically only in the thesis. In Dataset 1 the compliance was on average 81% (SD= 21%, range= [23% 99%], N=16). For Dataset 2 the compliance was on average 74% (SD=17%, range= [39 95%], N=17). For Dataset 3 the compliance was on average 85% (SD=14%, range= [49 99%], N= 24).

4.5.1.1   Compliance: Dataset 1

The compliance results with Dataset 1 and Dataset 2 can be biased since the participants took part in the study and may have felt more obliged to wear the device. However in the Dataset 1 three-quarters of the available data were collected outside the study during normal assisted living. Since the telemetric actigraphy system had been in use in the institute before the study the recordings were longer than the actual study (434 days on average SD= 64 days) which made it possible to study compliance outside the study period. For Dataset 1 the out-of-range information was not available (information was not included in the study data available) and all the time periods when the data were not available were considered as non-compliant and thus can underestimate the compliance some compared to Dataset 2 and Dataset 3.

4.5.1.2   Compliance: Dataset 2

In Study II the compliance of 36% was reported for Dataset 2. The reported low compliance (36%) was related to the research software (back-end) problem, which was used to collect the activity data on a server computer at the facility. For an unknown reason the server was shut down during summer vacation, causing a four-week loss of activity data in the second subgroup. The activity data were collected successfully from 76% of all the days during the first subject group participation before the data loss. The reported compliance of 74% was achieved for the whole subject group when the problem period was excluded from the analysis. If the 'out of range' period was totally excluded the compliance was on average 68% (SD=18%, range= [36% 92%]). Including the out of range periods in the compliance analysis can thus overestimate the results slightly.

4.5.1.3   Compliance: Dataset 3

The compliance results with Dataset 3 are based on the real-world data since the study was an archival study and no actual study period was organized. Compliance was on average 65% (SD=29%, range= [4% 98%]) if time periods outside the base-station range were considered as non-compliant. The average recording period was 494 days with 267 days standard deviation.

4.5.1.4   Summary of compliance

According to the datasets the compliance was between 74–84% on average. The results reported here are based on very long-term data and collected in real-world settings. In practise nurses and care personnel can motivate the users to wear the device as often as possible. In related work it was also concluded (Paavilainen, Korhonen & Partinen 2005) that one of the most promising aspect of the device is its high compliance due to the alarm features; both manual and automated. According to the results there are no major differences between research period compliance and real-world use compliance. The results reported agree with related literature according to which 20–30% of data were expected to be missing. It should be noted that there was some deviance in the compliance rates between the subjects which should be considered during monitoring. For example, there was only 47% data available (or even less) for some subjects in Dataset 3 which might not enable reliable trend monitoring. This was not studied in the dissertation.

4.5.2   Validity of the actigraphy parameters for older adults

In this section results on validity of activity levels, circadian rhythm parameters and sleep patterns recorded with the telemetric actigraphy are presented. The sleep/wake classification has been validated in a related study (Lötjönen et al. 2003) and by this thesis' focus on studying validity of long-term sleep patterns compared to self-reports.

4.5.2.1   Validity of activity levels from actigraphy for older adults

Dataset 2 includes self-reports on physical exercise (minutes a day) and sleep, and daily pedometer recordings in parallel to the actigraphy data. For studying the validity of activity parameters we compared the telemetric actigraphy's activity parameters with the pedometers step count and the self-reported exercise on the group level. In Study III the days which contained step count and at least two hours of actigraphy data during the time period between 10 AM and 8 PM. were included in the comparison analysis. Spearman's correlation between the average daily activity (DAY ACT) and step count was 0.62 ($P<0.01$, N=608) on the group level.

In Study III it was also found that the self-reported exercise and the steps are positively correlated (RHO=0.257, P<0.01, N=1153). However DAY ACT (RHO=-0.139, P<0.01) and number of actigraphy data points (no data due to off wrist or out of the base station range) during the day (RHO=-0.132, P<0.01) have small negative correlation with self-reported exercise. This might indicate that the "exercises" have been performed when the actigraph was out of the base station range.

In addition to daily measures, seven days average of the parameters were included in the analysis (Study III). The averaging is supported to be used with actigraphic monitoring to increase the reliability of the measurements. The correlations between the averaged parameters, which were included in Study III are presented in Table 4 (extended from Study III). At least three days of data from the seven-day period was required for averaged value calculation. Days with more than three hours of actigraphic data during the day were included.

Table 4: Seven-day averaged activity parameters Spearman correlation coefficient matrix from Study III material.

Variable	Steps	Exercise	Daytime activity
Exercise	0.379** N=83		
DAY_ACT	0.482** N=67	-0.224 N=75	
Out of range	0.098 N=83	-0.065 N=109	0.072 N=75

*P<0.05, **P<0.01

According to the results the telemetric actigraph's activity level value gives a reasonably good estimate on daytime activity level when compared with daily step count for assisted living residents on the group level (strong correlation in daily measurements). There were no major changes between daily and seven-day averaged data in the correlation. However, with averaged data the connections between time spent outside the facility and objective activity measures were no longer statistically significant. The results suggest that, if many of the physical activities take place outside the facility the DAY ACT can underestimate the daytime activity level.

4.5.2.2 Validity of circadian rhythms parameters from actigraphy for older adults and middle-aged subjects

In the thesis we compared the selected circadian rhythm parameters between telemetric and traditional actigraphs with Dataset 4. For parameters utilizing passive/active classification (IS, IV, RA, L5 and M10) the threshold value of three (epoch > 3 was considered as active) was selected based on the correlation and error comparison analysis. The threshold values of two and three produced the best and almost equal results when compared to other threshold values (0, 1 and

4). The selection of three as a threshold value was influenced by the sleep-wake classification thresholds suggested for older adults. However the differences are very small between the two thresholds. For example, IV correlation was 0.914 and 0.918 with a threshold value of two and three. In the publication where these parameters have been included (Studies V and VI) we have used the threshold value of three (3). Although we did not utilize a separate test set in the study we consider that there is no major danger of overfitting the model and we believe that the results would be similar with a separate test set.

In the comparative analysis between the telemetric actigraph and the standard actigraph, the time periods for the parameter calculation were the same for the devices and missing data from either of the devices were removed from both of the recordings. Table 5 presents the Pearson correlation coeffients and mean absolute error between the devices for Dataset 4 and for the two subgroups in Dataset 4. The epoch of the standard actigraph was classified as active if any activity was detected, that is, the epoch value over zero which is utilized in the related literature (Carvalho-Bos et al. 2007, Lim et al. 2011).

Table 5: Pearson correlation coefficient (r) and mean absolute error (MAE) between the telemetric actigraph (Vivago) and traditional actigraph (Actiwatch). Standard deviation (SD) of error is given. Results are reported for all data (N=28), for middle aged (N=13) and for older adults (N=15).

Parameter	All data R	MAE±SD	Older adults R	MAE±SD	Middle aged R	MAE±SD
IS	0.91	-0.03±0.07	0.84	-0.03±0.09	0.97	-0.03±0.05
IV	0.92	0.04±0.08	0.92	0.06±0.08	0.94	0.01±0.07
RA	0.62	0.06±0.16	0.44	0.09±0.18	0.97	0.04±0.14
L5	0.50	-1.8±4.0	0.20	-2.6±4.7	0.75	-0.83±2.9
M10	0.88	-2.7±5.1	0.80	-3.5±5.7	0.91	-1.8±4.1
ACROPHASE	0.96	32±93	0.98	11.2±82.2	0.96	55.5±101
ACORR	0.64	0.11±0.08	0.46	0.15±0.08	0.86	0.07±0.06
CRS	0.61	0.13±0.08	0.52	0.14±0.08	0.75	0.11±0.06

IV, IS, M10 and acrophase have very strong correlation (Table 5) between the two devices, that is, the agreement between the methods is very good. L5, RA, CRS and ACORR correlations are moderate on the subgroup level. One possible reason for the differences is due to the different dynamics of the devices in the lower-level activities. The telemetric actigraphy is reported to sense movements, for example, originating from the joints close to the wrist (Lötjönen et al. 2003). The telemetric actigraphy seems to overestimate the autocorrelation 0.1 on average. There results indicate that telemetric actigraph has very good validity to estimate especially IS, IV, M10 and phase of the activity rhythm when compared to a traditional actigraph. The correlation is slightly lower for older adults, which can be

related to the frequent absence of the middle-aged group's daytime actigraph data.

4.5.3 Reliability of the actigraphy parameters for older adults

4.5.3.1 Test-retest analysis of actigraphy parameters for older adults

As stated in Chapter 2, based on the reliability of a measurement one can make conclusions about whether, for example, the intervention effect is significant or not. When studying reliability, the most typical evaluation measures are the typical error and the retest correlation (Hopkins 2000).

We studied the test-retest reliability of the different actigraphy parameters by observing percentage of standard error of the measurement between two data points with varying data lengths similar to related research (Van Someren, Riemersma-Van Der Lek 2007). The analysis has not been earlier performed for non-demented assisted living and nursing home residents or with the telemetric actigraph. Two consecutive fourteen-day-long periods of actigraphy data were selected for each subject with good quality data (that is, no major interruptions in the data when observed visually such as a recording missing for a whole day). The test-retest reliability of parameters were analysed for data lengths varying from one to 14 days (same week days in the comparison). The analysis helps to determine the optimal length for the parameter calculation and to estimate the precision at which the changes can be detected. We considered that if the periods are longer than two weeks we would be focusing on stability of the rest-activity behaviour more than the reliability of the analysis.

Reliability analysis results are visualised in Fig. 9 Twenty cases had required 28 days of good-quality data in Dataset1&2. Seventeen subjects' data were included in Dataset 3. The datasets were analysed separately since the actigraph version differed between the studies and from the combined dataset (Dataset 1&2) subjects with dementia were excluded. Older adults with dementia can have distinct rest-activity patterns (Paavilainen et al. 2005). The time between 12 PM and 6 AM was used when calculating TST, AWEKN and NIGHT ACT since bed time annotations were not available for the whole period. The timestamps for the night-time are similar than those used in the related research (Paavilainen et al. 2005). Median percent error is given in the figures as the distribution of the error is positively skewed. The parameters are divided into three subfigures; circadian rhythm parameters, night parameters and day parameters.
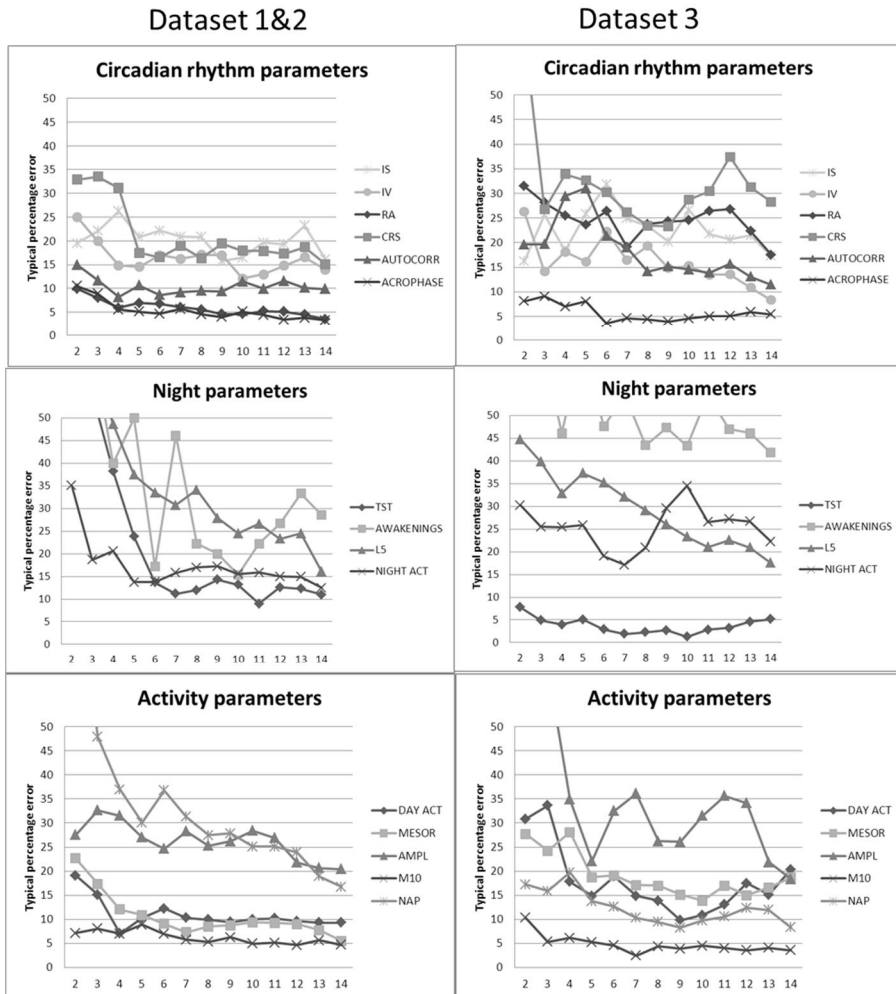
Figure 9: Test-retest reliability results: median percent error for Dataset 1&2 and Dataset 3. In the x-axis are given number of days used in the analysis and in the y-axis are median percent error between 0 and 50 %.

4.5.3.2   Observations from the test-retest analysis

Circadian rhythm parameters

IS error does not decrease almost at all if the window length is increased. The typical percent error is close to 20 or 30%. This suggests only small improvement if the data window length is increased, for example, over seven days. IV error decreases about 70 percent when the window length is increased. IV reliability benefits from data periods longer than seven days especially with Dataset 3. RA

behaves slightly differently in the two datasets. Improvement becomes small for Dataset 3 after about a week-long data sample. Error percents are higher in Dataset 3 than in Dataset 2.

CRS error stabilizes after a five-day-long recording period for Dataset1&2. CRS error even increases after a nine-day-long recording period for Dataset 3. AUTO-CORR error decreases until a 14-day data window for Dataset 3. Similar progress is not visible in Datasets1&2 in which AUTOCORR reliability is stable with five-day-long recordings. Acrophase error behaves very similarly in both datasets. The error stabilized after a week-long recording. It still should be remembered that the 'bias' in acrophase is high. For example with the acrophase of value 15:00 will five percent error be 45 minutes.

In general, median percent errors of the parameters are higher in Dataset 3 compared to Dataset1&2. Causes for the difference are not analysed. We however note that Dataset1&2 do not include demented subjects, whose day-to-day rhythm stability is found to vary more compared to subjects without dementia.

Activity parameters

The test-retest error for daytime activity decreases when the data window length is increased to one week. After this period the benefits are small for most of the activity level parameters. Mesor behaves similarly in both datasets and benefits even for two-week-long recordings (error 10–20%). For Dataset1&2 as well, amplitude benefits from long recordings. For Dataset 3 error of the cosinor amplitude is not robust and varies a lot when the window length is increased. This was not studied further.

M10 and napping error benefit from longer recording periods. Especially for datasets1&2, improvement with two-week recording periods is well visible. Most of the activity parameters benefitted from a week-long recording period and some benefitted even from a two-week long recording period. M10 and daytime activity level have the smallest error percent (5–10%).

Night-time parameters

Total sleep time error decreases for both datasets until one-week-long recordings, after which the improvement is modest. However the constant bedtime can have an effect on the results. Awakening benefits from longer recording periods, but especially for Dataset 1&2 the error varies notably, which is not visible in Dataset 3. Error in Dataset 3 for awakenings is high (>40%)

L5 error decreases almost linearly when the data window length is increased. Night-time activity reliability does not increase in these datasets for over one-week-long recordings and in the Dataset 3 results the reliability of the night-time activity even decreased for recordings lasting over a week. Errors, especially in parameters describing restlessness and fragmentation of the sleep, are high and do not benefit as much as other parameters for longer recordings. The constant analysis window can have an effect on the results when compared with the parameters utilizing a sleep diary for bed times.

Summary

Especially IS and CRS tend to have quite high error in Dataset 3 (20–30%) compared to other circadian rhythm parameters. Autocorrelation behaved the

most robustly in this sub-analysis. Percent error was below 15% for most of the circadian rhythm parameters. Awakening test-retest error was high compared to other parameters and varied a lot. The typical percent errors for most of the sleep parameters were between 15% and 25%. Activity parameters' error decreased stably as the recording length increased. The only exception was cosinor analysis amplitude in Dataset 3, in which the error varied a lot depending on the length of the recording.

It has been suggested that changes of 1.5 to 2.0 times the standard error would imply a reliably sight of change (Hopkins 2000). Since most of the parameter errors were less than 20%, the changes of 30–40% would be real and not related to measurement variance (that is variance of behaviour). For example, with Dataset1&2 when subjects were divided into better- and worse-functioning groups, IS values were 0.57 and 0.36, respectively for 7- to 14-day recordings. If, for example, an individual change would be likewise (that is 33%) it would be close to two times the typical error. Whereas, if the change would only be 0.10 it could be due to a normal behaviour variance. One outcome of this analysis would be alarm thresholds for different parameters in health monitoring of similar indices. The sensitivity of a telemetric actigraph to detect changes in longitudinal data is discussed further in Section 4.5.4.4.

4.5.4   Actigraphy parameters' associations with physical functioning for older adults

In this chapter we will present results on the association between the telemetric actigraphy parameters and physical functioning estimates. The results with Dataset 1 and Dataset 2 are mostly on the group level. With Dataset 3, sensitivity of the parameters to detect changes in the functioning status on group and individual levels has been analysed. Table 4 presents measures and variables which were included in the analysis. The ADL instrument utilized in Dataset 1 and Dataset 2 include 14 questions on limitations in basic and instrumental daily activities. The ADL instrument in Dataset 3 consisted of careful professional assessment of a resident's personal hygiene, toileting, locomotion and eating. Dataset 2 included functional performance tests in addition to ADL. See 4.2 for more details on the instruments.

4.5.4.1   Actigraphy parameters' association with activities of daily living estimates for older adults on group level

In Study VI (combined data with Dataset 1 and Dataset 2, excluding subjects with dementia) ADL was statistically significantly associated (Bonferroni corrected) with activity level (cosinor MESOR, R=-0.49, P< 0.01) and with night-time activity variance (NIGHT ACT, R=-0.69, P < 0.01). ADL had a trend with housing rhythm correlation (HOUSE, R=-0.44, P < 0.1) suggesting that subjects with worse functioning tend to have less-similar activity rhythm with the facility activities . In addi-

tion, subjects with worse functioning had higher 24h autocorrelation (more stable activity rhythm) than subjects with better functioning.

In Dataset 3 (Study V) ADL was statistically significantly correlated (Bonferroni corrected) with day-to-day stability (IS, RHO = -0.70, P <0.05) and with the strength of the rest-activity rhythm (CRS, RHO = 0.78, P < 0.01). This indicates that more stable and stronger rhythm was associated with better functioning status in nursing home residents with and without dementia. Correlation between ADL and IS diminished greatly when it was controlled for dementia rating (RHO=-0.20).

In Study III and IV with Dataset 1 ADL has statistically significant association with out of range duration (RHO= -0.67, P < 0.01) meaning that subjects with better functioning were more often outside of the facility area. In addition, ADL had a trend with night activity (NIGHT ACT, RHO = -0.48, P < 0.1) and with Daytime sleep (RHO=0.41, P < 0.1). This suggests that older adults with better functioning tend to sleep less during the daytime and tend to have more variance in activity during night-time.

Dataset 3 included subjects with dementia, which is different from Dataset 1 and Dataset 2 analysis in Studies III, IV and VI. Dementia level was controlled in the analysis of Study V.

4.5.4.2 Dataset 2: Actigraphy parameter association with physical performance test for older adults

In Study IV we created clusters representing a summary score for the performance tests and ADL questionnaires due to a lack of such a score. The score (that is the ordered clusters) is selected to represent the physical functioning status (1=best, 4=worse). According to Spearman correlation (no Bonferroni corrected) analysis NAP (RHO=0.57, P<0.05), DAY ACT (RHO=-0.55, P<0.05) and Out of range (RHO=-0.66, P<0.05) have a statistically significant correlation with the summary score. This suggests that less daytime sleep, more daytime activity and more visits outside the facility were associated with better functioning status for assisted living facility residents.

4.5.4.3 Dataset 3: Actigraphy parameters' association with physical functioning instrument score for older adults with and without dementia.

Table 6 presents Spearman correlation coefficient between the actigraph variables and functioning estimates for Dataset 3.

Table 6: Weighted and partial rank order correlation coefficient (weighted/rank) controlled for cognitive performance scale between functioning status estimates (resident assessment instrument, RAI) and actigraphic parameters (n of samples = 31, n of subjects =16). Average (standard deviation) values of the actigraphy parameters are given for subjects grouped according to median of the functioning status estimate (RAI ADL).

RAI measure / Actigraphy measure	RAI Activities of Daily Living (ADL)	RAI Pain	RAI Depression Rating Scale	RAI ADL smaller than or equal to median (N=9)	RAI ADL larger than median (N=7)
Cosinor mesor (MESOR [epoch])	-0.20/-0.26	0.38/0.43	0.45/0.48	10.3 (5.7)	11.3 (10.6)
Cosinor amplitude (AMPL [epoch])	-0.35/-0.21	0.45/0.48	0.27/0.39	12.4 (7.4)	9.2 (8.6)
Cosinor acrophase (PHASE [time])	0.24/-0.28	-0.12/0.08	-0.11/-0.24	15:56 (1:27)	16:15 (1:45)
Inter-daily stability (IS)	**-0.70*/-0.20**	-0.04/-0.29	-0.54/-0.40	0.57 (0.19)	0.36 (0.15)
Intra-daily variability (IV)	0.60/0.45	-0.43/-0.37	0.22/0.11	0.63 (0.23)	0.83 (0.19)
Relative amplitude (RA [hourly epoch ratio])	-0.58/-0.10	-0.11/-0.44	**-0.67†/-0.60**	0.55 (0.18)	0.35 (0.17)
Circadian rhythm strength (CRS [epoch ratio])	**0.78*/0.59**	-0.08/-0.02	0.37/0.13	0.30 (0.17)	0.57 (0.22)
Daytime sleep/passive amount (NAP [minutes])	0.29/0.38	-0.45/-0.56	-0.28/-0.42	98 (90)	111 (83)
Total sleep time (TST [minutes])	-0.13/0.38	-0.25/-0.60	-0.50/-0.53	550 (104)	490 (177)
Number of awakenings (AWEKN)	-0.17/0.29	0.11/-0.26	-0.45/-0.49	1.7 (0.9)	2.1 (1.5)

†$P<0.1$, $P<0.05$, **$P<0.01$,

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4.5.4.4 Longitudinal case analysis and examples (Dataset 2 and Dataset 3)

The sensitivity of the actigraphy parameters to notice changes in function was studied in Study V via case analysis (Dataset 3). In total, eight cases were included in the analysis. Table 8 presents the correlation analysis results for cases which had changed in ADL during actigraphic monitoring. The measurement period was 449 days on average. Case 19 had a different correlation direction between the actigraphy parameters and ADL compared to other subjects.

According to longitudinal case correlation analysis in Study V, IS, IV, CRS and NAP had the most systematic correlation with ADL score over different cases. Table 7 presents visually estimated absolute and percentage changes for the selected parameters in the case analysis. According to the test-retest analysis, a change of approximately 30% in actigraphy monitoring parameters would indicate an actual change in behaviours. For most of these parameters the change was above the 30% when functioning status was changing. For cases 15 and 19 there were no visually observed trend changes in daytime sleep behaviours.

Table 7: Estimations of IS, CRS, NAP and IV changes during the case recording for cases 8, 15 and 19. Percentage change has been determined from the visually estimated change. RAI ADL progress is presented. Values in the parentheses are outside the actigraph recording period.

Parameter	Case 8	Case 15	Case 19
ADL	(5)-1–2-(5)	(2)-2–5–5	(1)-1–3-(3)
IS	0.4 -> 0.2 (50%)	0.6 -> 0.2 (60%)	0.4 -> 0.7 (70%)
CRS	0.4 -> 0.6 (50%)	0.4 -> 0.8 (100%)	0.3 -> 0.2 (30%)
NAP	400 -> 550 (40%)	no visible trend	no visible trend
IV	0.9 -> 1.2 (30%)	0.7 -> 1.0 (40%)	0.7 -> 0.5 (60%)
Recording days	489	478	487

In addition to group-level analysis in Study VI, two long-term case demonstrations were presented (Dataset 1&2). We noticed that for a subject with better functioning night-time actigraphy deviation (NIGHT ACT) correlated with daily sunlight duration (Spearman RHO= 0.21, $P < 0.05$); the shorter dark time at night during the summer was possibly making sleep more restless for the subject. A similar trend was not present in the data for a subject with worse physical functioning. For her, the outside temperature and daytime activity level (average of activity values between 8 AM and 8 PM) had a negative correlation (RHO= -0.25, $P < 0.05$) in the summer, suggesting that during the warmer days, the subject was more passive.

Table 8: Case analysis for associations between physical functioning assessment and actigraphy changes. Spearman rank order correlations (RHO) are given between actigraphic parameters and resident assessment instruments' activities of daily living Scale (RAI ADL). Only significant correlations (p < 0.05) are shown. RAI ADL scores are given in chronological order. RAI ADL assessments outside the actigraphy recording are presented in parentheses.

Case / Actigraphy measure	Length [days]	AMPL	RA	IS	IV	CRS	NAP	PHASE	TST	AWAKN	RAI ADL [scale]
#8, 89 years, non-demented	489	-0.62	-0.62	-0.64	0.69	0.57	0.70			0.54	(5)-1-2-(5)
#9, 88 years, demented	320	-0.62		-0.64			0.51		0.72	-0.57	5-6-6
#15, 101 years, non-demented	478	-0.41	-0.34	-0.46	0.34	0.53	0.26			-0.38	(2)-2-5-5
#19, 88years, demented	487		0.55	0.54	-0.44	-0.38	0.29	-0.48			(1)-1-3-(3)
#27, 91 years, non-demented	470			-0.52	0.74	0.57	0.53		0.31		(0)-2-0

5. Discussion

5.1 Results relation to objectives

The compliance and feasibility of the telemetric actigraph in older adult population

According to Datasets 1, 2 and 3 the typical compliance of the continuous telemetric actigraph data tend to be between 70% and 90%. These findings agree with related research (Biswas et al. 2009, Howell et al. 2010, Mathie et al. 2004, Davis, Fox 2007). However residents' habits of wearing the device differed. For example, the compliance varied between 49% and 99% among subjects. According to the results the compliance in the nursing home residents was slightly higher compared to assisted living facility residents. We did not study factors behind these differences. The sensitivity of the processing methods for missing data was not evaluated in the thesis. The amount of missing data was reported in the studies.

The subjects in Dataset 2 were participating in a home health monitoring study and took into use other health technologies in addition to the telemetric actigraph, which might have had an effect on compliance. The fact that the subjects in the study did not have other motivation factors, such as a feeling of safety due to the alarming properties, might have effected on compliance. There were no statistically significant differences between demented and non-demented subjects in compliance in Dataset 3. In real use, a facility's personnel can influence compliance, for example, with a help of the system's automated 'off-wrist' alarm feature.

The varying levels of compliance need to be noticed, for example, in the algorithm development of the assessment instruments and when interpreting the scores. For most of the subjects the compliance was reasonably high to allow trend analysis of the long-term actigraphic data.

Identify and develop new processing methodologies describing the wearer's habitual rest-activity patterns

In the related research several actigraphy processing methods were presented. Especially for sleep and activity, rhythm quantification methodologies were diverse, which is why we decided not to exhaustively develop new ones. For the analysis in Studies V and VI non-parametric, activity count-based indices (IV, IS and RA), cosinor analysis and autocorrelation were selected since these were

most commonly utilized in similar research and covered the rest-activity rhythm widely. In the selection we were especially interested in parameters which are not strongly related to the device epoch's absolute value. Good examples are the acrophase of the cosinor analysis and non-parametric indices IV, IS and RA. However, for the calculation of the non-parametric indices we had to define an optimal threshold value for performing an active-passive minute classification. The threshold selection was based on the comparative analysis (4.5.2.2) between the traditional actigraph and the telemetric actigraph. The results showed very high correlation for IV and IS with the selected threshold (an epoch value over three was considered active). The good agreement between the two devices facilitates generalizing of the results. In addition, the device-specific Circadian Rhythm Strength parameter was included in the comparative analysis between actigraphy parameters and physical functioning. There was no major risk of overfitting, but it would be encouraged to perform the threshold optimization with the newest device versions and with longer recordings.

The development of the stimulus-response actigraphy parameters has not been included in analysis of thesis objectives so far. Utilizing the common activity curve for the parameter creation was not a result of literature review. We noticed when analysing Dataset 3 that several residents had repeated daytime activity patterns which most likely were due to facility activities such as meals. We hypothesized that by averaging all the residents' activity patterns, common activity patterns of the facility would be revealed. By comparing the individuals' activity patterns with this facility's common curve, a novel stimulus-response parameter could be added on the group analysis.

The decision of utilizing the weather variables in the stimulus-response analysis was more obvious, since the circadian rhythm entrainments are quite well studied and, for example, the role of light as a stimulus for circadian rhythms is well known. The analysis in the thesis including weather variables does not contain actual parameter extraction but we rather focused on studying the correlations with the subjects' actigraphic data and potential meaning of these correlations. Further work on this objective in the future would be reasonably easy due to the open data programs, for example, with the weather data.

The actigraphy processing methods depicting sleep characteristics has been widely studied and the selection of the processing methodologies was clearer. The challenge when calculating some of the sleep parameters was the lack of sleep diary in Dataset 3 in cross-sectional and in longitudinal analysis. Although in the related research's fixed time between 12 PM and 6 AM have been utilized, we selected a wider range (between 9 PM and 8 AM) according to visual observations in Studies V and VI (Paavilainen et al. 2005). The fixed time frame might have an effect on the results with the sleep parameters. This was not studied in the thesis. In addition, we added in the analysis standard deviation of the actigraph during the night-time, since it had the strongest correlation with the sleep stages in the related research with the device (Lamminmäki et al. 2005).

Association between physical activity level and health have been studied quite extensively, which is why only some activity level parameters were included in the

analysis. The daily activity level and cosinor analysis alikes (amplitude and mesor) have been widely utilized in the related research.

Validity of the actigraphy-based methods in quantifying the habitual rest-activity patterns

Activity level

In Study III the primary objective was to study if daytime napping and sleepiness-related features are associated with a person's physical functioning and physical activity behaviour. In this thesis the correlation matrix was extended to cover the association between the daily activity level measures (4.5.3). The results showed that self-reported exercise and actigraphy's daytime activity level did not correlate. In general, all the correlations between the different activity parameters are mainly moderate, which suggests that they all tell about a slightly different area of activity. The strong agreement between steps and daytime activity on the group level imply that the actigraphy's average daytime epoch value reasonably well estimates the activity level status of a subject. The telemetric actigraph's daytime activity level estimate is affected by the out-of-range time when the activity is not stored and different scaling of lower-level activity when compared to traditional actigraphs (Lötjönen et al. 2003).

Sleep characteristics

The sleep-wake classification of the device has been validated in an earlier study (Lötjönen et al. 2003). Dataset 1 and Dataset 2 were collected with the same type of device as in the original work. Dataset 3 had a newer version of the device whose sleep-wake classification validation has not been published in a scientific forum.

The presented long-term sleep validation Study I included subjects from stress rehabilitation and not older adults. We included in the thesis a comparison analysis between self-reported TST and the device-originated TST between 11 PM and 7 AM for Dataset 2. The main result of this analysis suggests that the agreement between the two methods increases when the data is averaged (in this case over a week), which also supports the related literature and the thesis findings. Another future research topic is to gain information on how self-reports and objective sleep measures should be combined to give indication of potential unhealthy sleep patterns. Individualized knowledge on the residents sleep could be utilized in care design and in long-term monitoring.

Activity rhythms

With Dataset 4 we compared the processing methods of the activity rhythms between the telemetric actigraphy and widely utilized actigraphy (Lötjönen et al. 2003). IV, IS and acrophase from the cosinor analysis have very high correlation (over 0.9) and small error between the traditional and the telemetric actigraph. These results indicate that other reported results in the thesis which utilize these parameters generalize well. However autocorrelation and night-time activity patterns (L5) agreements were lower (below 0.6), which should be considered when comparing the results. Especially, the lowest five-hour average active minutes (L5)

had only a weak correlation for older adults. We suspect that slightly different dynamics of the device in low activity level could have caused the difference. This suggests that some results based on low-level activity (especially during night) might not generalize well.

Reliability and long-term robustness of the actigraphy processing methods

For studying reliability of the actigraph's parameters the test-retest analysis was made. The analysis demonstrates the characteristics of the point measures and guided the analysis performed especially in Studies V and VI. For older adults without dementia the analysis has not been published in related research for actigraphs. We encountered similar results than previously reported for insomniac and for persons with dementia (Van Someren 2007). Our results show that especially IS and CRS tend to have quite high percent error in Dataset 3 (20-30%). The number of awakenings varied the most in both datasets between the two measurement points. Typical percent error for most of the sleep parameters ranged between 15% and 25%. Especially activity parameters' error decreased systematically when the recording window was increased. Only exception was the cosinor analysis' amplitude in Dataset 3. It should be noted that the percent error was reported, which is affected by the absolute value of the parameter. The results supports the related research indicating that most of the actigraphy parameters' reliability increases until seven-day-long measures and some of the parameters even benefit from longer measurements in heterogeneous older adult populations (Van Someren 2007). It should be pointed out that the error describes variance in behaviours rather than in measurement technique.

According to the literature, real change in measures should be greater than 1.5 times the standard error (Hopkins 2000). A change of 30% in, for example, IS and IV would indicate a real change in activity behaviours based on the encountered results. The differences between the two functioning groups in Study VI (group 1: ADL=20.1 (4.7), Group 2: ADL=37.3 (5.6)) were 17% for IS difference, 29% for IV, 32% for CRS, 22% for HOUSE and 46% for MESOR. If similar changes would happen in longitudinal data for IV, CRS and MESOR we could expect something changing in physical condition as well.

Associations of actigraphy-based habitual rest-activity patterns with physical functioning of older adults

In Study VI, Dataset 1 and Dataset 2 was combined and data for subjects with dementia were excluded from the analysis. The selection was done since a reasonable amount of actigraphy studies including persons with dementia already exist, and it has been noticed that dementia can affect a person's circadian rhythm system independently (Paavilainen et al. 2005). The sample size in Study VI (N=36) for analysing correlations between actigraphy parameters and functioning assessments was acceptable according to power analysis.

In Study VI subjects' higher daytime activity and more variance in activity patterns were associated with a better functioning status. According to related research (Zuurbier et al. 2015) poorer day-to-day stability (IS) and more fragmented daily activity (IV) was associated with all-causes of mortality. The results indicate a similar trend with the activity fragmentation than the related research. However results in Study VI indicate that the similarity of the activity behaviour between the days would increase when the functioning status worsens in the heterogeneous older adult population. It has been reported that typically older adults' daily rhythm becomes more stable which could protect them from functioning decline, which might reflect on the results in Study VI (Huang et al. 2002).

The results in Study VI also show that lower housing rhythm correlation might indicate a deteriorating condition after a certain functioning level. This might have been caused by the fact that the dependent people are more stimulated by the facility activities, and if they are not able to react to such stimuli (facility rhythm is normally very stable) anymore it would indicate an even further decline.

The stimulus-response indicators' association with the functioning presented in VI have not been reported earlier in related research. Since a significant correlation between the housing rhythm index and physical functioning exists we suggest that the topic should be considered in future related research. However we note that for subjects in better physical condition the housing rhythm might not describe an external stimulus well. Stimuli such as weather variables might be better suited for analysis with the independent subjects. In the case of demonstrations we noticed that two subjects with very different functioning states reacted differently to weather changes.

In Study V with Dataset 3 the analysis methodologies were similar to Study VI. However, the subject group in Study V also included persons with dementia. In addition, the material included longitudinal data from the actigraph and the functioning estimates. The encountered association between the telemetric actigraphy at the group level was what was expected according to the literature (for example (Carvalho-Bos et al. 2007, Paavilainen et al. 2005)). More stable and stronger circadian activity rhythm was associated with better functioning in the repeated sample analysis. In addition, less daytime passivity/sleep and lower intra-daily variability were associated with higher functioning status according to case analysis. However for one subject the longitudinal correlations were opposite compared to other cases. The magnitude of the changes in actigraphy parameters in the case analysis as well agreed with the related research and group level findings. According to the case analysis in Study V the circadian rhythm parameters behaved more consistently than sleep parameters when compared to changes in functioning. The results in Study V suggest that long-term actigraph monitoring may detect reliable trend changes in several activity behaviours reflecting functioning and health changes in the nursing home environment. Due to the variance in the parameters the actigraphy parameters' values should be inspected against historical data, for example, during the last six months or even a year. According to the reliability analysis results the changes in parameters scores (two-week-long

actigraphy recordings) should be at least 30% for indicating an actual change in health.

In Studies III and IV (Dataset 2) the actigraphy parameters were compared with different performance tests, self-reports and their combinations. In Study IV day-time passivity/sleep, daytime activity behaviours, and night-time restlessness were considered important indicators of functioning status. It was interesting to notice that although the number of steps (measure via a pedometer) had an association with the most of the functioning tests, only actigraphy parameters were selected in the multivariate model for estimating the holistic functioning score. In addition, the information on how much time subjects spend outside the facility was connected with self-reported functioning and lower extremity strength. This result suggests further study of context information added to the actigraph type of solution when long-term health is monitored.

The WHO proposes use of qualifiers (from zero to four) to grade the severity of the problem in different ICF categories to which the objective measures could be transformed. An ICF Core set exists for sleep disorders and for geriatric rehabilita-tion, which both include sleep functions. However, we could not encounter studies involving actigraphy with ICF directly. Large datasets are collected including actig-raphy and ICF components (e.g. SOF and MrOS), and it might be relevant to create Qualifier codes for actigraphy output for specific targets such as geriatric rehabilitation. This might facilitate the use of objective measurements, for exam-ple, in rehabilitation effect monitoring.

Limitation of the studies

The datasets included in the thesis are relatively small. For example, when studying the association between physical functioning and actigraphy parameters power analysis suggests using 30–40 subjects at minimum. The study population in the datasets are somewhat heterogeneous, especially when Dataset 1&2 were combined. The heterogeneity as well helps to understand how the activity and sleep patterns associate with physical functioning at various levels of health state. Dataset 3 lacked a sleep log during the study which prevented the use of some of the sleep parameters in the analysis. The lack of controlling factors like infor-mation on interventions along the longitudinal data limits the results' reliability. However, we encountered only a couple of studies including as long actigraphy recordings, which highlights especially the value of analysis of the thesis. In some of the sub-analyses, multiple comparisons were not controlled and the population was smaller than it should be according to power analysis. These results are given less focus in the thesis.

The case analysis including weather information is more a prelude to the topic and systematic analysis would be needed. The housing rhythm parameter extrac-tion method is in a draft phase and would need further iterations and analysis.

The telemetric actigraphy's minute-to-minute epoch value is proprietary, which limits the generalizability of the results of some parameters such as the activity amplitude. In addition, the telemetric actigraph's version is different between Da-

taset 3 and other datasets, which might cause some variance in the results and was the reason the test-retest reliability was analysed separately for Dataset 3.

Since there were lot of other technologies included in the study of the compliance and usability in Dataset 2, the actigraph was not prioritized and especially the usability could be studied more extensively in the future. In addition, the feedback from the nursing personnel would be important to collect and analyse.

For more independent subjects, the fact that the telemetric actigraph does not store the epoch values when the device is outside the facility can affect the parameter values and thus the results to some extent.

5.2   Contribution of thesis results to the field

The compliance of the telemetric actigraph is typically between 70–90% even in very long-term recordings for nursing home and assisted living facility residents. However, there tends to be distinct compliance patterns in the study population. The system's possibility to inform the care personnel on the compliance and the social alarm features most likely affect compliance positively in real settings.

The reliability of point measured actigraphy parameters' improves up to a week of recordings and some parameters benefit from even longer measures for the study population similar to in this thesis. In addition, the potential amount of missing data for some users (that is compliance) suggests using longer recordings, such as two weeks in this case.

Our results indicate that for the heterogeneous older adult population without dementia, the activity level during the day and night would correlate best with a physical functioning estimate on the group level. The correlations are moderate or strong. For the nursing home population including subjects with and without dementia, circadian rhythm parameters (especially IV, IS and CRS) correlate best with the physical functioning assessments in cross-sectional and longitudinal data. The correlations are now strong. For subjects with a better functioning state tend to have less inter-daily variance (IV), better day-to-day similarity (IS) and stronger circadian rhythm (CRS). Especially the longitudinal analysis is very seldom presented in the related research. The magnitude of the change in the parameters in the case analysis was as expected according to cross-sectional analysis. In addition, the evaluated change is real according to reliability analysis.

Since the associations between physical functioning and activity behavioural patterns slightly differed depending on the study population we recommended monitoring activity level, rhythm strength, similarity and variability simultaneously. Especially IV, IS and acrophase results are generalizable to other actigraphs according to comparative validation analysis between the traditional and the telemetric actigraphs. Sleep pattern measures were not found to associate significantly with the physical function in the presented studies.

We developed a novel method for estimating external stimulus (in this case facility common activities) effect on the rest-activity behaviour which was found to associate with the functioning status with a similar strength than physical activity

level measures. Although the phenomenon is not yet studied extensively, the results suggest that it provides a novel way to inspect a well-established measuring modality (actigraph) and is related to physical functioning among assisted living facility and nursing home residents without dementia. However, according to inspecting two case examples the stimulus might affect people with different physical functioning states differently.

Suggestion for future work

According to the encountered results and lessons learned in Studies I–VI, we propose following topics of interest for future research.

- More longitudinal studies are needed to better understand if the actigraphy parameters behave in a way similar to cross sectional analysis as observed in Study V. This type of study is absent especially for non-demented assisted living facility and home care subjects. We also need to understand if it is typical that for some subjects the parameters change against the cross-sectional data.
- Although the actigraphy study has a long history, novel processing concepts such as stimulus response relationship indicators can add a new research branch to the area.
- Additional context information such as automatically extracted sleep logs, visits outside, weather and ambient data are already collected in actigraph systems and could be utilized in smart ways when studying connections in long-term objective measurements and preclinical indication of health.
- We utilized facility averaged activity patterns in individual analysis but it would be beneficial for care organization as well to have group-level analytics for facilities for evaluating their performance.
- We need to better understand ways to utilize the information which these systems provide in care design and care processes. Such research is ongoing, for example at Tigerplace, Missouri, where home health monitoring data is utilized to alert oncoming health problems in advance and the alerts are addressed by the facility nursing personnel.

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Long-term subjective and objective sleep analysis of total sleep time and sleep quality in real life settings

Proceedings of the 29th Annual International
Conference of the IEEE EMBS
Cité Internationale, Lyon, France
August 23-26, 2007.

SaC02.4

Long-Term Subjective and Objective Sleep Analysis of Total Sleep Time and Sleep Quality in Real Life Settings

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Abstract—Sleep quality is one of the key elements of the human health status. By observing sleep patterns we can gain information about personal wellbeing. Consumer electronic sleep analysis solutions are now available for use in long-term conditions. In this study we compare different measures for total sleep time and sleep quality. We analyzed visually long-term sleep data collected with actigraphy, sleep logs and ambient sensors to gain more reliable results and compared these results to each single method's output. Correlations of visually analyzed total sleep time between actigraphy total sleep time (correlation coefficient (r) = 0.662, $p < 0.01$) and sleep log total sleep time ($r = 0.787$, $p < 0.01$) were high. Also comparison between subjective and objective sleep quality was analyzed and small, but significant correlation was found ($r = 0.270$, $p < 0.01$).

I. Introduction

SLEEP is one of the most important daily factors for wellbeing, and disturbed sleep patterns are showed to be in connection with some harmful events such as stress or cardiovascular diseases [1], [2].

Nowadays there are methods to perform sleep analysis automatically. Polysomnography (PSG) is the golden standard of sleep analysis. However, PSG is not practical for collecting long-term sleep data at the moment. Therefore, actigraphy is considered to fit better in the long-term scenario of the personal sleep analysis. Actigraphic signal is normally collected with a wrist unit placed on non-dominant hand. 95% percent of agreement in sleep-wake classification between PSG and actigraphy has been achieved [3]. For example, the Standards of Practice Committee of the American Sleep Disorders Association has supported the use of actigraphy in the assessment of sleep disorders [4].

However, there are problems when collecting activity signal in a domestic environment. For example, people can stay still on the couch watching television before going to bed or they can forget to put actigraphy on again after a shower. These inactivity periods in many actigraphy sets will be most likely classified as sleep. In addition to the actigraphic signal, detailed logs of sleep-wake periods and artifact-related information should also be collected to improve data validity outside the laboratory. Reliability of sleep analysis is important not to end up into false hypothesis according to inaccurate parameters. Also the actigraphic signal should be collected over several nights to gain more reliable results. [5][6]

We used the The Vivago® WristCare (IST International Security Technology Oy, Helsinki, Finland; http://www.istsec.fi/) continuous telemetric monitoring of the user's activity to obtain long-term sleep data at home together with ambient sensors and objective sleep-related parameters (sleep logs). To improve reliability and accuracy of the automatic sleep analysis a neurologist visually analyzed sleep data from the actigraphic signal with the help of ambient sensor's and sleep log's information. We also evaluated a connection between objective and subjective sleep quality over this long-term study.

II. Methods

A. Study arrangement

We conducted a study including long-term personal health parameters in real life settings. Two user groups in vocational rehabilitation were selected to a three-month study period. The users had a two-week rehabilitation period during the study outside their homes. Otherwise all the monitoring was done at home. Together with the measurements, the users made daily health-related observations concerning their sleep time and quality.

B. Description of the used health monitoring system

We built a personal health monitoring system which included different ambient and wearable sensors (see Fig.
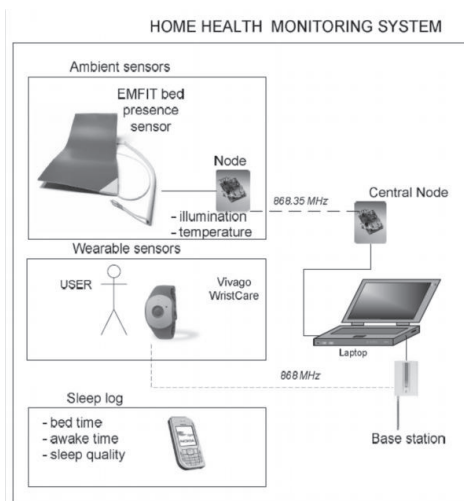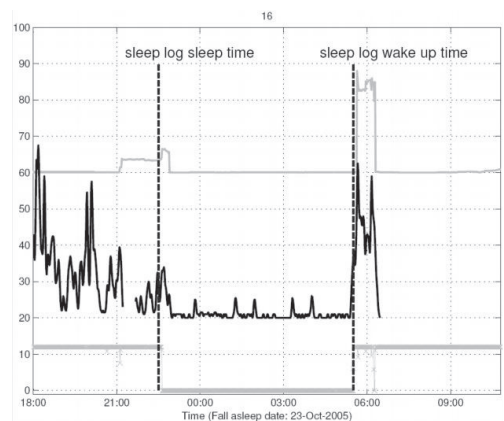
Fig. 1: System for data collection

Fig. 2: Example of combination from the collected signals (the topmost grey is illumination, vertical dashed lines are from sleep logs, black is actigraphy, and the lowest grey is bed occupancy information). All the signals are scaled to fit to the figure.

1). System collected data automatically to a laptop computer which was situated at home. Used devices utilized wireless data-transmission techniques. Every week, the laptop computer automatically sent data to a server.

The Vivago® Wristcare is a tele-actimeter and was used daily to collect personal activity signal from the non-dominant wrist. The Vivago® Wristcare system includes algorithms to analyze personal sleep patterns. For example Lötjönen *et al*. reported The IST Vivago® Wristcare being capable of performing the automatic analysis of sleep-wake classification with similar accuracy to actigraphy (Actiwatch) when comparing to PSG [7]. The Vivago® WristCare's wrist unit communicated with a base station which was connected to the laptop computer collecting the activity signal. The Vivago® WristCare (actigraph) can also detect whether it is on the wrist or not, which is an advantage compared to traditional actigraphs and helps to avoid misclassified sleep periods [5].

We also collected bed occupancy sensor (BOS) data (Emfit Ltd, Vaajakoski, Finland, http://www.emfit.com/). Bed sensor was connected to the laptop computer with a wireless network module (Node) including illumination and temperature sensors [9].

In addition to these methods, users made self observations from their sleep time and sleep quality (sleep logs). They marked bed time, wake-up time and sleep quality from 0 to 10 (ordinal number) by utilizing newly developed mobile phone software, Wellness Diary [10].

C. Sleep parameters and statistical analysis

Prints with figures (Fig. 2) from actigraphy and combination of signals (illumination, temperature, BOS and sleep log) were visually analyzed and, in addition, a neurologist gave an estimate of the sleep quality (ordinal number from 1 to 5) based on the actigraphic signal [11]. Low signal level actigraphy indicating enough deep sleep were graded higher than those with more restless actigraphy profiles. This was achieved with five profile models retrieved from earlier comparisons with PSG [7]. The arousals and awakenings were also counted. Finally, the sleep analysis results were transformed manually to electronic form for the further analysis with a Matlab (Version R14) based software.

We compared the visually analyzed total sleep time (TSTSCORED) with three different methods: 1) automatically calculated TST from the actigraphic signal (TSTACT), 2) the time in bed calculated from the sleep log (TSTLOG), and 3) the bed occupancy time between the hours of 20 and 10 according to BOS (TSTBOS). Visually analyzed sleep quality (QSCORED) was compared with: 1) the sleep quality from sleep logs (QLOG), 2) the mean (AVEACT), and 3) the standard deviation (SDACT) of the

TABLE I
TOTAL SLEEP TIMES (TST) OF AND ERRORS BETWEEN THE DIFFERENT METHODS IN MINUTES (N = 728)

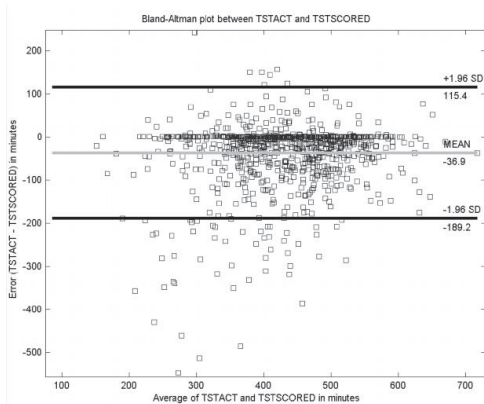| Parameter	Mean	SD	Range
TSTSCORED	449	86	161 – 719
TSTACT	411	99	23 – 677
TSTLOG	461	82	120 – 696
TSTBOS	446	146	0 – 816
Error between TSTACT and TSTSCORED	-37	77	-513 – 243
Error between TSTLOG and TSTSCORED	12	55	-290 – 243
Error between TSTBOS and TSTSCORED	-14	142	-614 – 365

Fig. 3: Bland-Altman plot for comparing methods TSTSCORED and TSTACT

Fig. 4: scatter plot between TST_scored and methods TST_log and TST_act

actigraphic signal over the night time. With comparison of different TST results we used the linear Pearson correlation and with the sleep quality the non-parametric Spearman correlation by utilizing SPSS (Release 14.0.1).

We have also compared TST before work day and non-work day to find out weather the work schedule has an effect on the different methods. However, we have not divided results according to gender due to the small amount of the participants.

III. RESULTS

17 users (14 females and 3 males) participated in the study with average age of 54 years (SD = 5.4). Two users reported using sleeping pills occasionally, but they were not excluded from the analysis. User group 1 (8 users) took part in the study in the summer and group 2 (9 users) in the autumn 2005. Users collected data cumulatively from 1406 days. 983 nights from these had sufficient data for the visual sleep analysis (TSTSCORED) with an average of 58 nights per user, but data from 728 nights were used in the analysis of TST containing information from all the used methods. We were able to analyze QSCORED from 884 nights. Two users were excluded from the sleep quality analysis due to the lack of the actimeter signal.

As seen from Table 1 TSTLOG slightly overestimates, while TSTACT and TSTBOS underestimate. There is no

TABLE II
THE PEARSON CORRELATIONS OF TOTAL SLEEP TIME (TST) BETWEEN THE DIFFERENT METHODS (N ALL DAYS = 728, N WORK DAYS = 374, N NON-WORK DAYS = 354)

Parameter	All days	Work days	Non-work days
TSTLOG	0.787**	0.777**	0.773**
TSTACT	0.662**	0.697**	0.609**
TSTBOS	0.302**	0.274**	0.257**

** Correlation is significant at the 0.01 level

clear relationship in the error between TSTSCORED and TSTACT as seen in Fig. 3. However, TSTACT seems to underestimate more when TST gets shorter.

The Pearson's correlations of TSTLOG and TSTACT compared to TSTSCORED are strong as seen in Table 2. TSTACT overestimates TST seldom, whereas TSTLOG is more stable when compared with TSTSCORED (Fig. 4). Differences in correlations between the work day and the non-work day are small (Table 2).

Connection between TSTLOG and TSTSCORED remains steady when comparing data over different months. However, the second user group has slightly better correlations between TSTSCORED and TSTLOG (user group 1: r = 0.711, p < 0.01; user group 2: r = 0.813, p < 0.01), and between TSTSCORED and TSTACT (user group 1: r = 0.483, p < 0.01; user group 2: r = 0.758, p < 0.01). The errors between the methods and TSTSCORED do not differ significantly between the two user groups.

QSCORED has a strong negative correlation with AVEACT (r = -0.802, p < 0.01) and SDACT (r = -0.613, p < 0.01). In addition, QLOG has small but significant positive connection (r = 0.270, p < 0.01) with QSCORED. Also TSTSCORED and QLOG had a connection (r = 0.260, p < 0.01) according to this data. However, only 6 out of the 15 users had significant correlation between QSCORED and QLOG, and 6 out of the 17 users between TSTSCORED and QLOG.

IV. DISCUSSION

Our objectives were to improve accuracy of the sleep analysis based on the actigraphic signal, the sleep logs, and the ambient sensors' output in the long-term health monitoring study at home. After the visual analysis, we compared this approach to the sleep log markings and the automatically calculated values from the actigraphic signal and the bed sensor.

One still has to remember that we calculated TST straight from the time stamps of falling asleep and awakening, which ignores arousals during the night. This may be a reason for the differences between TSTSCORED and TSTACT. Summer and summer holidays can be one cause of the small differences observed in the correlations of TST

between the two user groups.

TSTLOG overestimated TST due to the fact that the users actually marked their time in bed instead of sleep time. However, strong correlation between TSTLOG and TSTSCORED implies a good reliability of the simple sleep log in long-term use. TSTLOG connection to TSTSCORED did not change as a function of the time as it was noted to be possible by Ancoli-Israel et al. when parents kept sleep logs from their children's sleep behavior [5].

Deviation of the error between the methods is high which emphasizes aggregating the actigraphy output over several nights as stated also elsewhere [4,5]. Now, however, collected data were fragmented and not many long and constant periods would have been achieved for statistical analysis.

Weaker correlation of TSTBOS to TSTSCORED suggests that the bed occupancy information does not describe the sleep time very accurately, but could be used to increase the control of the actigraphic measurement.

Significant differences between the nights before the work day and the nights before the non-work day did not exist which also supports the reliability of long-term home usage of the Vivago® WristCare.

QLOG correlated with QSCORED and TSTSCORED statistically significantly, but less than half of the user's QLOG markings did correlate with the visually analyzed sleep parameters. This was predictable due to the simple estimation from the sleep quality, and the high inter-individual differences in activity profiles. The subjective sleep quality is also known to differ from the objective quality [12].

Objective data of the sleep quality is needed to evaluate sleep quality in long term conditions especially when analyzing possible sleep problems. The advantage of the actigraphic analysis is that it gives direct information of the changes in the sleep profile, number of awakenings and long arousals which form part of the sleep quality parameters. This is possible especially if personal long-term signal trend is considered.

V. CONCLUSION

High correlations between TSTACT and TSTSCORED implies that the Vivago® WristCare system can provide an accurate sleep pattern estimation in home-like environment in long-term conditions but it should be controlled as Sadeh *et al.* stated e.g. combining it with bed time and illumination information [4].

In addition, simple sleep logs are reliable methods to collect simple sleep parameters in long-term conditions according to this data.

These results imply that we can improve accuracy and reliability of objective sleep analysis by combining the actigraphic signal with the simple sleep logs and cheap ambient sensors' output.

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Compliance and technical feasibility of long-term health monitoring with wearable and ambient technologies

▶ Compliance and technical feasibility of long-term health monitoring with wearable and ambient technologies

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Summary

We developed a system consisting of both wearable and ambient technologies designed to monitor personal wellbeing for several months during daily life. The variables monitored included bodyweight, blood pressure, heart-rate variability and air temperature. Two different user groups were studied: there were 17 working-age subjects participating in a vocational rehabilitation programme and 19 elderly people living in an assisted living facility. The working-age subjects collected data for a total of 1406 days; the average participation period was 83 days (range 43–99). The elderly subjects collected data for a total of 1593 days; the average participation period was 84 days (range 19–107). Usage, technical feasibility and usability of the system were also studied. Some technical and practical problems appeared which we had not expected such as thunder storm damage to equipment in homes and scheduling differences between staff and the subjects. The users gave positive feedback in almost all their responses in a questionnaire. The study suggests that the data-collection rate is likely be 70–90% for typical health monitoring data.

Introduction

Telehealth and personal health systems might enable early intervention when there are negative changes in a person's health status. Health screening studies in a home-like environment have a long history[1] and different measuring devices are widely utilized.[2–4] However, there are relatively few studies concerning compliance with long-term health monitoring in real life settings.[5–8] In a review of home telehealth, Koch reported the need for better usability and better wireless tools.[9] As a person's compliance with monitoring is a critical factor in any successful health monitoring approach, more studies should be carried out to identify the design factors and monitoring characteristics which contribute to high compliance during long-term monitoring.

We have therefore studied the technical feasibility and user compliance with long-term health monitoring in two different user groups. For this purpose, we developed a system for long-term health monitoring during everyday life.

Methods

The system consisted of both wearable and ambient technologies designed to monitor personal wellbeing for several months during daily life. Users could also report their subjective self assessments of stress and other activities such as physical exercise.

A wrist-worn wireless activity monitor (IST WristCare, Vivago, Helsinki, Finland) was used to observe a person's activity and sleep/wake pattern. This monitor has been reported to perform sleep/wake detection with similar accuracy to actigraphy, which is the most commonly used alternative to polysomnography in sleep analysis.[10] The users were able to view their activity data from a laptop computer with special software. The monitor has been shown to be a sensitive method of detecting changes in the health status of elderly people.[11] The wrist unit used a wireless link to communicate with the base station, which was connected to a laptop computer located in the user's home (Figure 1).

Air temperature and the intensity of light in the bedroom were collected with a wireless network module (node) containing temperature and illumination sensors.[12]

Vital signs during bed time were collected using an electromechanical film sensor (Emfit Ltd, Vaajakoski, Finland). The variables measured were heart rate,
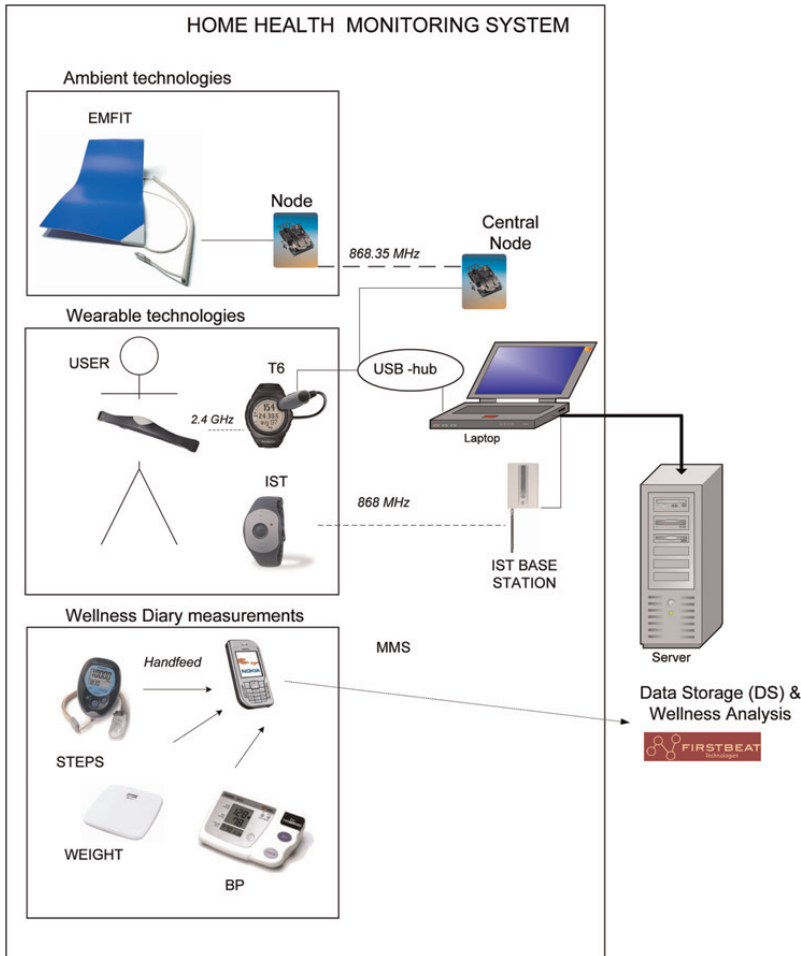
Figure 1 System overview. The user inserted health measurement readings into the Wellness Diary by hand. MMS = Multimedia Message Service, EMFIT = bed sensor, IST = actigraph. T6 = wrist top computer for heart-rate variability

movements and respiration rate (Table 1). A bed sensor was installed below the user's mattress. It behaved in the same way as the Static Charge Sensitive Bed (SCSB) which has been used previously in sleep analysis.[13]

Beat-to-beat heart-rate variability (HRV) was detected with a heart rate belt. This was connected wirelessly to a wrist top computer (model t6, Suunto Oy, Vantaa, Finland).[14] We used the beat-to-beat heart rate data to analyse the load of the autonomic nervous system of a user. The user was instructed to start the measurement in the morning and continue it until the evening at least three times a week. The user transferred the recorded beat-to-beat data to a laptop computer via a USB-cable.

Manager software

The beat-to-beat data were analysed using software (Firstbeat Technologies Oy, Jyväskylä, Finland) to segment and

categorize the HRV data into stages of stress, relaxation and exercise.[15,16] The software was stored on the server computer (Figure 1).

A freely available mobile phone application (Wellness Diary, Nokia Corp., Helsinki, Finland; see http://research. nokia.com/research/projects/WellnessDiary/) was used to record wellness related self-observations and to give objective graphical feedback to the user. It has been well accepted and frequently used in an earlier study.[17] The Wellness Diary was used to store daily sensor readings and self assessments (Table 1). However, if the subject was not able to use the Wellness Diary, we offered them an alternative, storing the data on paper.

There were three other monitoring devices: a pedometer (Walking style II, Omron Corp., Kyoto, Japan), a blood pressure monitor (705IT, Omron Corp.) and a bodyweight scale (OBH Nordica Finland Corp., Vantaa, Finland).

Table 1 Description of measured features with technologies used in the study

Measurement	Variables
Vivago WristCare: continuous (once/minute)	-Activity signal
	-Usage (on/off wrist)
	-Sleep/wake detection
Node: continuous (once/minute)	-Illumination [maximum, minimum]
	-Temperature
Emfit: continuous (once/minute)	-Presence
	-Amplitude
	-Breathing frequency
	-Breathing amplitude
	-Heart rate
Suunto t6: 3 times a week	-Beat-to-beat heart rate variability
	-Pressure altitude (0.5 Hz)
Firstbeat HEALTH: reports from the beat-to-beat heart rate variability data	42 different variables, e.g.
	-Relaxation time
	-Stress time
	-Average heart rate
Wellness Diary: intermittently during the day	-Morning blood pressure [systolic BP, diastolic BP, pulse]
	-Evening blood pressure [systolic BP, diastolic BP, pulse]
	-Stress self-assessments [stress, tiredness, anxiety, tension]
	-Sleep [quality, length]
	-Steps [number of steps, calories burned, distance]
	-Exercise [duration, type, intensity, distance]
	-Weight
	-Sickness [type, description]
	-Visit to doctor [source, diagnose]
	-Treatment [name, dosage]

The data from these devices were stored in the Wellness Diary manually by the user.

Data collection

Data from the different monitoring devices were collected on a laptop computer which was located in the user's home. The laptop computer automatically transmitted the data to a database via a dial-up connection. In addition, the users

were instructed to send the data from the Wellness Diary once a week. The diary used the Multimedia Message Service (MMS) to transmit the data to the database via email. The users also reported on paper whether each day was a working day, a day off or sick leave. The paper records were collected at the end of the study.

Data quality was controlled manually with the help of graphs generated from the database to indicate missing or poor quality data (Figure 2). If users forgot to send the diary data then they were reminded to do it. All the measurements were requested to be done daily except the HRV measurement which was done twice during the week and once at the weekend (Table 1). An example of the collected data is presented in Figure 3.

User feedback questionnaire

After the study the users filled in a usability questionnaire, which included 35 items. The first 21 were 5-point Likert scale items related to the usability and acceptance of the system. The scale also included a 'no comments' option. Table 2 lists the 17 questions used in the analysis which were collected from both subject groups. The questionnaire also included seven items related to perceived usefulness (a 5-point scale from useful to useless) and seven items related to the perceived burden of the different measurements (a 5-point scale from easy to burdensome).

Subjects

We selected two different user groups for the study: working-age subjects participating in a vocational rehabilitation programme and community-dwelling elderly people. All the subjects participated voluntarily and the study was approved by the appropriate ethics committee.

Working-age subjects

The first study group consisted of subjects participating in a vocational rehabilitation programme to improve their
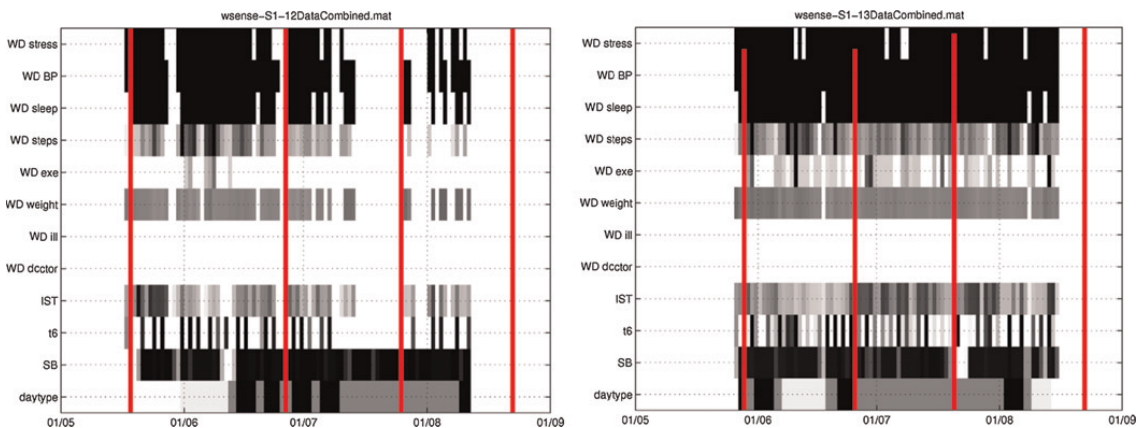
Figure 2 Collected data quality graphs with Derogatis Stress Profile markings. The recordings show fragmented data (left) and good quality data (right)
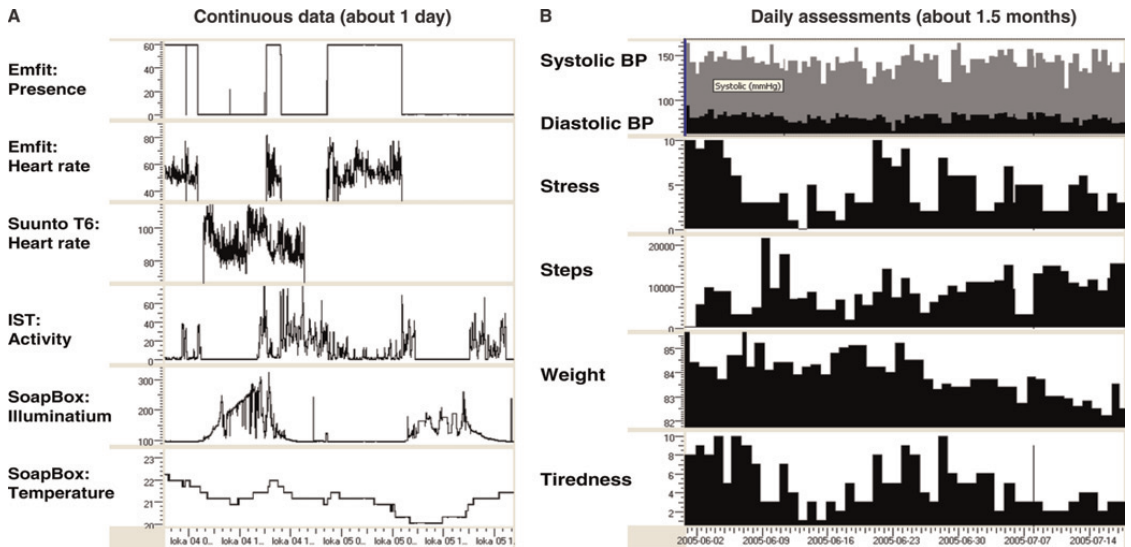
Figure 3 Example of collected data (A) from the technologies which measured continuous data and (B) from the technologies which stored results once a day, including self-assessments (e.g. stress and tiredness)

working ability, i.e. these users had experienced some decline or a significant risk for a decline in their working ability. A typical entry criterion to the rehabilitation programme was signs of burnout according to the Bergen

Table 2 Results from the usability-acceptance questionnaire

Statement	Working-age subjects* Positive/ negative (%)	Elderly subjects* Positive/ negative (%)
1 Heart rate belt felt uncomfortable.	24/65	67/22
2 Use of pedometer was unobtrusive.	88/6	94/6
3 Pedometer was difficult to use.	88/6	82/18
4 Vivago wrist unit felt uncomfortable.	47/35	44/38
5 Blood pressure meter was easy-to-use.	100/0	94/0
6 Daily blood pressure measurements were disturbing.	88/12	82/6
7 Bed sensor bothered me in the bed.	65/12	88/6
8 Daily measurement routines felt laborious.	41/35	71/18
9 I felt my privacy offended by the system.	71/18	82/12
10 The computer was silent enough.	82/12	94/6
11 I felt the system was disturbing at home.	59/29	94/0
12 Daily measurement of weight felt natural.	88/0	94/6
13 Use of the Wellness Diary needed lot of practice. Use of the paper form was clear (elderly subjects)	76/18	82/12
14 Making the Wellness Diary entries was difficult	88/12	
15 Stress assessment statements were understandable. Assessing the vigilance was easy (elderly subjects).	41/18	53/12
16 The Wellness Diary graphical feedback was useful. The feedback from the paper form was useful (elderly subjects).	76/0	82/9
17 Sending the Wellness Diary data was easy. Writing down information on the paper form felt natural (elderly subjects).	71/6	73/13

*Proportions of positive and negative answers

Burnout Indicator (BBI).[18] Subjects were recruited to the study among rehabilitation programme participants, i.e. participation in the study did not affect their participation in the programme. Exclusion criteria were severe coronary artery disease, hypertension with more than two medications, beta-blockers, diabetes demanding insulin treatment, some disorder of the central nervous system like Parkinson's disease, hyperthyroidism with medication, polyneuropathy or major depression. Users were from northern Finland and the rehabilitation period was arranged in the Rokua and Kajaani rehabilitation centres. Users were recruited by letter and interviewed afterwards when they completed the BBI. The study duration was three months for each subject. The users completed the Derogatis Stress Profile questionnaire every month to quantify their physiological stress.[19]

At the beginning of the study the users had the system at home for two weeks. They then came to the rehabilitation centre for two weeks (Figure 4). After the rehabilitation period they continued in the study at home for two months. Setting up the system in the subject's home included face-to-face guidance on how to perform the measurements, how to use the equipment and how to view the results from the laptop computer. They also received a written manual about operating the system. During the study, users could contact a researcher if there were any problems with the system.

A total of 17 subjects were recruited during 2005. There were two subgroups: the first started in the spring ($n = 8$) and the second in the autumn ($n = 9$) (see Table 3). There was one dropout from the first group due to a long vacation, but the other subjects completed the study successfully.
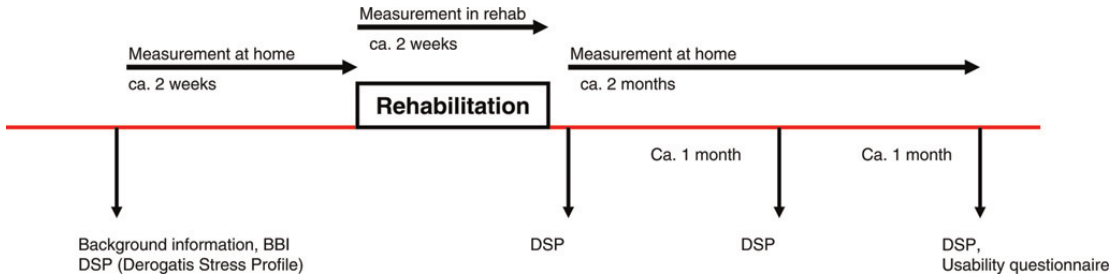
Figure 4 The study process with the working age users

Elderly subjects

The second study group consisted of elderly subjects who lived in an assisted living facility which provided accommodation and rehabilitation services for elderly and disabled people. During the study, they participated in a health intervention designed to increase their physical activity. The inclusion criteria included volunteering to participate in the intervention and the present study, and having self-reported sleep problems, loneliness or low physical activity. The exclusion criteria were having an acute disease, being in the active degeneration phase of a chronic disease, having a known disturbing event like surgery during the study, a neurological disorder which prevented them from using the system's components, dementia, any physical limitation that prevented their participation in the guided physical exercise or depression without a medication.

We used the 15-item Geriatric Depression Scale (GDS-15),[20] the Mini-Mental State Examination (MMSE),[21] a basic and instrumental activities of daily living questionnaires (ADL-IADL)[22] and a questionnaire (Terveysseula) to evaluate safety and suitability of exercise for each subject personally (UKK institute, Tampere, Finland). A physiotherapist performed functional capacity tests at the start of the study to define suitable exercises for the subjects during the intervention, and at the end of the study to quantify the effect of the intervention. Participation in the guided physical exercise was provided for the subjects and attendance at these activities was encouraged (Figure 5). A user manual and a manual for their family or caregivers were provided.

Table 3 Demographic data

	Working age		Elderly	
No. of subjects	17		19	
No. of females	14		14	
	Mean	SD	Mean	SD
Age, years	55	5	78	3
BMI, kg/m^2	26.8	3.3	28.6	7.9
BBI	49.2	12		
MMSE			27.3	3.3
ADL			17.5	6.3
GDS-15			2.5	1.6

The participants used a paper form (Figure 6) instead of the Wellness Diary to collect self-assessments and sensor results. We considered that the use of smart phones by the elderly subjects was not appropriate in the study. In contrast to study group 1, data were collected manually every second week because of the lack of an Internet connection (the telephone lines were directed through a call centre, and it was not possible to achieve a dial-up connection). Wrist activity data (IST) were collected using base stations situated around the facility collecting data from several users instead of a laptop computer.

A total of 19 elderly subjects was recruited in 2006. There were two subgroups: the first started in the spring (*n* = 9) and the second in the summer (*n* = 10) (see Table 3). There were three dropouts in the second subgroup. One of the subjects contracted a fatal encephalitis caused by herpes simplex; the second had eye surgery which prevented his participation after the surgery; the third had spent a lot of time outside the home and wanted to give up before the study period ended.

Results

The working-age subjects collected data for a total of 1406 days. The average participation period was 83 days (range 43–99) (see Table 4). One subject felt that the heart rate monitor was too uncomfortable to use and gave up at the beginning of the study. A summary of the collected data is provided in Table 4. The summer vacations affected the data collection (see the example in Figure 2), so that more data were missing during that period. However, some subjects took the system with them outside the home, e.g. to a summer cottage. The HRV data were collected for a total of 374 days, with an average duration of 9 hours per day (range 0–21).

The elderly subjects collected data for a total of 1593 days. The average participation period was 84 days (range 19–107) (see Table 4). For the elderly subjects, the heart rate monitor turned out to be too demanding and we decided to omit it during the early phases of the study. Thus, heart rate monitoring was provided only to the subjects who were interested in it. For these subjects, the HRV data were collected for a total of 12 days with an average duration of 10 hours (range 3–18).
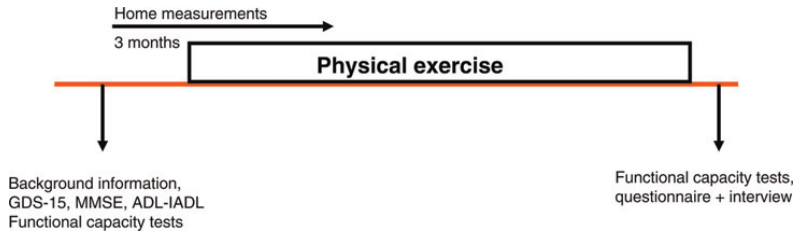
Figure 5 The study process with the elderly subjects

Two significant technical problems occurred during data collection from the elderly subjects:

(1) Our data collection software running on a laptop was not developed to work as a service under the Windows operating system. Hence, it terminated when somebody logged out from the computer. The elderly care facility personnel were accustomed to log out from their computers whenever finishing their computer usage, and we did not realize this. Furthermore, although the personnel were instructed to collect the data from the laptops every second week, in practice this collection occurred less often. These factors caused the loss of six weeks' of the ambient data from eight people in the first subgroup. After proper education of the personnel responsible for the second subgroup, 93% of the ambient sensor data were collected successfully;

(2) The Vivago Vista software, which was used to collect the activity data ran on a server computer at the facility. For an unknown reason the server was shut down during the summer vacation, causing a four-week loss of activity data in the second subgroup. The activity data were collected successfully in 76% of all days for the first subgroup.

User feedback questionnaire

All 17 working-age subjects and 16 out of 18 elderly subjects completed the user feedback questionnaire at the end of the study. In addition to this, the daughter of the older subject who died filled in the questionnaire which we included in the results because the daughter visited her mother (a subject) almost daily during the study and we considered the reported information to be valid. The results are summarised in Table 2. Only the subjects who had used the

Figure 6 Paper form for self-observations and measurement readings, which was used in the study with the elderly subjects

Table 4 Percentage of data obtained compared to that intended

	Working-age subjects		Elderly subjects	
	No. of days collected	% of intended data collected (SD)	No. of days collected	% of intended data collected (SD)
Measurements				
Vivago WristCare	1139		947	
Continuous*		30		36
Daily†		80		52
Emfit/ Node	1130		1157	
Continuous*		68		62
Daily†		80		65
Blood pressure	1220	86 (13)	1250	77 (22)
Steps	1050	74 (14)	1153	70 (22)
Weight	1065	75 (17)	1271	78 (19)
Assessments				
Sleep	1128	79 (15)	1280	78 (20)
Exercise‡	522	37 (18)	749	46 (28)
Stress (working age)/ Vigilance (elderly)	975	69 (20)	1267	78 (21)

*Continuous assumes that the data were available 24 hours a day
†Daily takes account of days when there were data available, even if it was only from a short period
‡Exercise information was measured from the exercise frequency

heart rate monitor answered question 1. Most statements had more positive answers than negative. Only the heart rate monitor usability was rated low. After converting the data into a 2×2 table (positive and negative) the response to the question about obtrusiveness (no. 11 in Table 2) differed significantly between the two user groups ($P = 0.018$). Responses to the other questions did not differ significantly. The questionnaires also involved statements on the Wellness Diary and the paper form usage (the analysis of data from the Wellness Diaries is discussed more detail elsewhere).[17] Both methods were rated positively. Psychophysiological assessments in the Wellness Diary and in paper format (stress and vigilance) were considered to be the most difficult items (Table 2).

In both groups, blood pressure (working-age subjects average 4.8 out of the maximum 5, elderly subjects 4.8), weight (working-age subjects 4.7, elderly subjects 4.6) and exercise (working-age subjects 4.4, elderly subjects 4.3) were considered to be the three most valuable variables by the users. The working-age subjects considered steps (1.1 out of the most difficult 5), bodyweight (1.1) and blood pressure (1.3) as the easiest to measure during the study. The elderly subjects felt that bodyweight (1.3), blood pressure (1.4) and exercise (1.6) were the easiest ones.

Experience

Some of the unexpected problems that were encountered during the study were:

(1) The low-power wireless connection between the sensors and the laptop computer turned out to be unreliable during long-term home usage. On two occasions users covered the central node with a metal object (e.g. headphones), which prevented the transmission so that ambient data were lost;

(2) A thunderstorm damaged one node unit and the USB ports of the laptop computer causing a break in the data collection;

(3) Six of the working-age subjects did not have a fixed telephone line which prevented them using a dial-up connection so that the user data had to be collected directly from the user's home. This delayed the detection of possible problems;

(4) If the user accidentally unplugged the USB hub, the data collection of the ambient sensors was interrupted;

(5) The data collection start up scheme for the heart rate monitor was complex. This caused some losses in data collection;

(6) Technical support required more time than we first expected and the education period necessary almost doubled from the time we had originally estimated (from 2 hours to 3.5 hours). In our experience, proper user education is critical to the success of the monitoring, and hence sufficient time and resources should be reserved for it.

Discussion

We studied the usability, compliance and technical feasibility of a health monitoring system consisting of both wearable and ambient monitoring technologies. Subjects from the two different groups, working age and elderly, accepted the system relatively well and their opinions about it were generally positive. The fact that the subjects were volunteers might have biased the results. It is known that user attitudes have a major effect on usage activity of the home health systems.[23] The daily routines were viewed as somewhat laborious, which is one drawback of long-term health monitoring. This highlights the importance of feedback from the system to the user. Detecting negative as well as positive trends in measured variables could give very important information for the clinician and for the user. Continuous monitoring enables the user to receive feedback earlier than with usual practice. The present study simulated data collection to personal health records, which are currently becoming available for the general public.

Bodyweight, steps and blood pressure measurements were considered to be the easiest and the most interesting variables to measure. This may be related to the fact that these measurements are already well known and the equipment is mature and easy-to-use. However, the elderly subjects felt that paper-based reporting of the exercise was easier compared to pedometer usage. This may be because pedometers are still complicated for elderly people to use with small screens and buttons. In addition, the standard pedometer did not work for some of the elderly subjects due to the difference in their gait compared to young adults. However, several elderly subjects considered the pedometer as very motivating for exercising. Hence, developments to make these sensors more convenient and more reliable with the special user groups such as elderly people should continue.

The quantity of collected data was similar to that reported in earlier studies. For example Mathie *et al.* succeeded in collecting 88% of intended measurement days with a wearable accelerometer.[5] Compared to our activity data (80% and 50% for the working-age subjects and elderly subjects, respectively) this is slightly higher, but our data collection was greatly influenced by the technical problem that occurred during the study, and was not related to compliance.

The rate for other measurements and self assessments was also reasonably high. Some 70–90% of bodyweight and blood pressure measurement activity has been documented in other long-term studies involving either healthy or sick persons.[2,6,8] Scherr *et al.* stated that computer-generated reminders can motivate users to carry on with measurements better than if no feedback is given.[6] We reminded users by contacting them only when they had not sent the data. During the study with elderly users the measurement data (especially the paper form) were collected manually from the users' homes, which might have worked as a motivator. We strongly recommend the use of a reminding technique when collecting health-related long-term data.

Although we used relatively mature and tested devices, we still encountered some technical problems with the monitoring and especially the communication and data collection technologies. Hence, online data gathering and system monitoring should have been better implemented (especially with the elderly users) to improve the quality of data. However, it should be noted that many of the problems were more related to human errors than to technical malfunctions.

The elderly subjects felt that the system and the measurements were less disturbing at home, which supports the statement of Korhonen *et al.* that the elderly are more willing to accept inconveniencies due to the monitoring system in order to maintain their independent living.[24] The working-age subjects emphasized the importance of feedback and the possibility of viewing their own data. This agrees with Fisk's statement that the control of one's own information is an important feature of a telehealth system.[25]

Although a research system was used in the present study we consider that the usability and non-system specific results such as technical support time management can be generalized for future practice. By integrating a range of wearable and ambient health monitoring technologies we were able to build a relatively acceptable and reliable home monitoring system at reasonable cost. In long-term health monitoring studies, small practical issues such as schedule differences between the patients and the staff, usually have a major effect on success. The present study suggests that the data-collection rate is likely be 70–90% for typical health monitoring data. Thus, missing values have to be considered in the analysis of any long-term health monitoring data.

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Connections of daytime napping and vigilance measures to activity behaviour and physical functioning

CONNECTIONS OF DAYTIME NAPPING AND VIGILANCE MEASURES TO ACTIVITY BEHAVIOUR AND PHYSICAL FUNCTIONING

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ABSTRACT
Ability to do different daily activities defines partly one's independency. We study older adults' daytime sleep behaviour (napping) with respect to user's physical activity behaviour and physical functioning. The daytime sleep behaviour was measured via self-reported vigilance, actigraphy and bed sensor. Nineteen users took part in the study for three months. Especially actigraphy napping feature was found to have statistically significant correlation to number of steps, daily activity and self-reported exercise. According to the data, daily napping habits can also tell about the user's physical ability level.

KEY WORDS
Actigraphy, bed sensor, daytime sleep, physical functioning, older adult

1. Introduction

Current demographic change (portion of the older adults in community is growing) is causing a lack in different resources and drives the research for new innovative solutions that enable successful aging. A physical ability to perform daily routines i.e. physical functioning is one of the corner stones of independent living. Automated, long-term monitoring of the physical functioning (functioning later on) at home environment could be beneficial. By taking preventive and rehabilitative actions early enough we could decrease potentially expensive future care needs and improve one's quality of life.

Functioning consists of several areas. For example, in the EUNAAPA project (EUropean Network for Action on Ageing and Physical Activity; http://www.eunaapa.org/) researchers collected information about measures/tests which professionals are using in evaluation of the functioning of older adults. They identified nine different areas of functioning or connected topics:

- physical activity level
- endurance
- locomotion
- balance
- mobility
- manual dexterity and gross motor coordination
- muscular strength
- common indexes

- ADL (activities of daily living)

We recruited older adults to participate in the three-month study. During the study, different health-related observations were collected daily in the home environment. The data collection equipment and setup is explained in details in [1]. From the collected data we studied which of these methods are sensitive to indicate the level of functioning or changes in that level. In this paper, we discuss findings related to daily sleep behaviour.

It has been reported that sleep disturbances like insomnia and daytime napping have higher prevalence among older adults compared to other population. In addition to age, there are other factors causing sleep problems such as health status, medications, social and physical behaviour, and living surroundings. Chasens et al reported that sleepiness seems to have negative effect on amount of physical activity of a relatively healthy community-dwelling older adult which again is one factor of the functioning [2]. According to Gooneratne (in [2]) sleepiness had a negative correlation with vigilance.

Poor sleep patterns can lead to excessive daytime sleepiness, which is associated with functional and cognitive decline together with a lowered amount of physical activity and exercise [2, 3]. Excess daytime sleepiness has been reported to be extremely common in nursing home residents. However, as Cochen [4] reported, the effects of sleep problems are not well known in very heterogeneous older populations. People with daytime sleepiness reported lower sleep quality and lower overall health. Due to high rates of symptoms of sleep disorders, Wilson suggested that screening for sleep disorders should be the new vital sign in medical care, especially in geriatrics (Wilson 2005 in [2]). Chasens concluded that sleep disturbances might have negative consequences to physical exercising and finally to functioning. However, more long term studies have to be conducted to gain more information on these dependencies.

In this study our objective is to find out if daytime napping and sleepiness related features measured via different wellness technologies tell about person's functioning and physical activity behaviour.

2. Methods

2.1 Measuring daytime napping and sleepiness

We used three observation methods which could be associated to daytime napping and sleepiness.

1) Actigraphy: Vivago is a wrist-worn wireless activity monitor (IST WristCare, Vivago, Helsinki, Finland, similar to actigraphy; www.istsec.fi) and can observe a person's activity and sleep/wake patterns 24/7. The method has been reported to perform sleep/wake detection with similar accuracy to actigraphy, which is the most commonly used alternative to polysomnography in sleep analysis. The Vivago (later on actigraphy) was reported to be highly sensitive to detect self-reported naps, although there were some discrepancies between individual algorithms which should be considered when no personalization of the algorithm is done [5]. The software related to the device offers minute-to-minute sleep/wake discrimination during the whole circadian. This classification data were used to calculate the daytime sleep features i.e. napping time.

2) Bed sensor: Vital signs during the bed time were collected using an electromechanical film sensor (Emfit Ltd, Vaajakoski, Finland; www.emfit.com). The bed sensor was installed below the user's mattress. The device detects time spend in bed with one minute resolution. This information is used to calculate bed sensor based napping time during the day.

3) Self-reported vigilance: The participants reported their daily vigilance on 5-point Likert scale (5 represents a very active day) on paper [1]. This measure was hypothesized to tell about the daytime alertness and its opposite, sleepiness.

For the actigraphy and the bed sensor data the circadian was divided to a daytime (10am to 8pm) and a night-time (8pm to 10am). Actigraphy day napping time is a direct sum of sleep/wake classification per minute during the daytime. The classification was obtained from the actigraphy's software. If the actigraphy data were collected less than two hours during the day this day's data were excluded from the analysis. If the sensor is off the wrist or out of the base station's range the activity data is not available i.e. collected. The two-hour limit is purely heuristic. The bed sensor's napping time is as well the direct sum of presence feature in the bed during the daytime (seconds in a minute).

2.2 Physical activity behaviour measures

During the study the participants reported daily the time they spent doing physical exercises (self-reported exercise); this did not include intensity information. If the subject did not report exercise for a certain day but reported something else in the diary (see [1]) self-reported activity was coded as zero minutes for these days. Steps were measured daily via pedometer (Walking style II, Omron Corp., Kyoto, Japan) and users wrote the result (number of steps) in the diary. An average daily activity measure from the actigraphy is used to describe the subject's total daily activity behaviour (average daily activity). For this feature four hours of the actigraph data is needed for inclusion. The average is calculated from the

Table 1
Description of the features

Measure	Description
Actigraphy napping time	Daily napping time calculated from the actigraphy's sleep/wake classification between 10 am and 8 pm
Bed sensor napping time	Daily napping time calculated from the bed sensors bed occupancy detection between 10 am and 8 pm
Self-reported vigilance	The subjects reported daily their self assessed vigilance in the 5-point Likert scale
Steps	Number of steps from the pedometer for each day, which the subjects wrote down in the diary
Self-reported exercise	The subjects wrote down their physical activity amount in minutes observed by themselves
Average daily activity	Average of actigraphy's minute-to-minute activity value between 10 am and 8 pm

absolute activity value from each minute given by the actigraphy's software.

These three activity measures are used in the analysis. The average daily activity and actigraphy napping features are not independent measures and we assumed they would be heavily related. Table 1 summarizes the features used in the analysis.

2.3 Physical capacity and health measures

Before the study period, a gerontologist interviewed the participants and collected information related to subjects' functioning and health. These items were:

- Mini mental state examination (MMSE); 0 to 30 (30 no memory problems)
- Activities of daily living (ADL): 15 to 60 (15 totally independent)
- Self rated health; 1 (good) to 5(poor)
- Current exercise amount; 1=no, 2=daily, 3=3-5, 4=1-2, 5=rarely
- Sleep; hours per night
- Geriatric depression scale (GDS-15); 0 (no depression) to 15 (extreme depression)
- Sleeping pills usage; <yes, no>

At the beginning and the end of the study, a physiotherapist evaluated the participants' functioning via several tests. The test set is developed by State Treasury for evaluating veterans' functioning. The items included in this set were:

- Hand grip test of both hands
- Balance test (Standing with feet together , Retrieving object from floor, Turning 360 degrees, Tandem stance, Standing on one foot)
- Chair Stand 5 times
- Crouch times: crouch as many times you can (max 50)
- Step height
- Walking speed of 10 meters

2.4 Analysis

The data were analyzed from three different perspectives:

- The users' daily data were pooled together, and connection between napping features and activity behaviour were studied. Case-wise correlations were also analysed. The exclusion criterion for case-wise analysis was more than 10 samples for each data pairs e.g. step and actigraphy napping time.
- The daily activity and napping features were averaged over seven days. Periods with three samples or more were included. Again the connection was studied.
- The napping features were averaged and standard deviation (SD) calculated for the first month of the study period and connections with the functioning tests in the beginning of the study are analysed. The same analysis was done for the data of the last month of the study period. More than nine samples from the month were required that the feature was included in the analysis.

2.5 Subjects and data

The study group consisted of older adults who lived in an assisted living facility which provides accommodation and rehabilitation services for older and disabled people. During the study, they participated in a health intervention designed to increase their physical activity (Fig. 1). The inclusion criteria were: volunteering to participate in the intervention and the present study, having self-reported sleep problems, and loneliness or low physical activity level. The exclusion criteria were: having an acute disease, being in the active degeneration phase of a chronic disease, having a known disturbing event like a surgery during the study, a neurological disorder which prevented subject from using the system's components, dementia, any physical limitation that prevented their participation in the guided physical exercise, or depression without a medication. The study was approved by the appropriate ethics committee.

The 19 older adult subjects (average age 78, SD=3, 14 females) collected data for a total of 1593 days. The average participation period was 84 days (range 19–107). We had two problems with the data collection during the study. 1) A wrong log off procedure shut down the manager software and caused six weeks loss of bed sensor data (excluding actigraphy data) from eight people in the first subgroup. 2) The actigraphy's software, which was used to collect the actigraphy data, ran on a server computer at the facility. For an unknown reason the server was shut down during the summer vacation (most likely caused by the renovation work done in the building), causing a four-week loss of activity data in the second subgroup.

3. Results

3.1 Daily napping and activity behaviour relationship

The napping features were not normally distributed (according to Kolmogorov-Smirnow test) and Spearman rank correlations were used in the analysis. There were statistically significant correlations between most of the three napping features (Table 2).

Table 3 presents the statistically significant relationships (Spearman) between the daily napping and the activity features.

3.2 Case-wise correlations

Between steps and actigraphy napping time there were three cases with statistically significant correlations similar to the pooled data. Between self reported exercise and actigraphy napping time there were two cases with significant negative correlation which differs from the pooled data findings. Nine out of 14 (five do not have actigraphy data) had significant correlation between average daily activity and actigraphy napping time, which was expected since the features are based on the same device data.

There were two cases with significant negative correlation between bed sensor napping time and steps, one case with positive correlation between self-reported exercise and bed sensor napping time, and two cases with negative correlation between bed sensor napping time and average daily activity.

For self-reported vigilance five cases have positive significant correlation with steps, four cases have positive correlation with self-reported exercise, and one case have positive correlation with average daily activity.

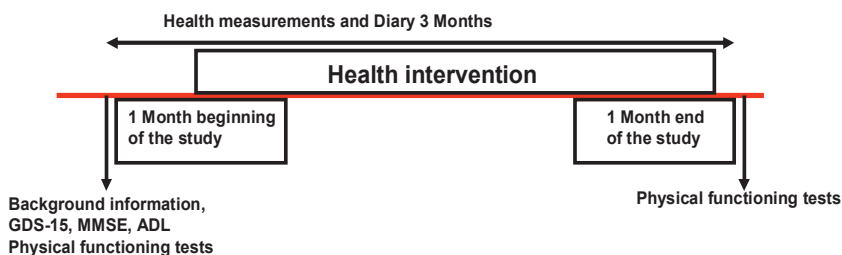There were no major changes in persons' health status

Figure 1: The study description

Table 2
Spearman correlation coefficients between daily
napping features

Napping feature	Actigraphy napping time	Bed sensor napping time	Self-reported vigilance
Actigraphy napping time N	- 536	0.547** 321	-0.221** 536
Bed sensor napping time N	0.547** 321	- 870	-0.124** 649
Self-reported vigilance N	-0.221** 536	-0.124** 649	- 1267

** Correlation is significant at the 0.01 level.

(functioning) during the study period. Hence the possible connection between features might be better present at the pooled data since there are differences between the subjects. However, a good measure is sensitive and reliable both on individual and on group level.

3.3. Seven-day average napping and activity behaviour feature relationship

Most of the seven-day average features are not normally distributed and Spearman rank correlation is used in the analysis. Concerning daily napping, a similar correlation remained than with the daily observations, although the connection between bed sensor and self-reported vigilance disappeared.

There was only one change in correlations between averaged daily napping features and activity behaviour compared to day to day analysis as the actigraphy's napping time and self-reported exercise statistically significant relationship disappeared (Table 4). However, the correlation is significant if parametric test is used.

Case-wise correlations were not calculated due to small amount of samples per case for the averaged data.

3.4 One month averaged napping data compared to functioning and health measures

Table 4
Spearman correlations coefficient between napping and
activity features (seven-day average)

Activity feature \ Napping feature	Actigraphy napping time	Bed sensor napping time	Self-reported vigilance
Steps N	-0.253* 83	- 74	- 138
Self-reported exercise N	- 42	- 106	- 167
average daily activity N	-0.702** 75	-0.586** 106	0.450** 67

** Correlation is significant at the 0.01 level.
* Correlation is significant at the 0.05 level.

Table 3
Spearman correlations coefficients between daily
napping and activity features

Activity feature \ Napping feature	Actigraphy napping time	Bed sensor napping time	Self-reported vigilance
Steps N	-.202** 521	- 650	0.159** 1078
Self-reported exercise N	,096* 536	- 710	- 1078
Average daily activity N	-,616** 608	-0.414** 321	0.263** 536

** Correlation is significant at the 0.01 level.
* Correlation is significant at the 0.05 level.

Beginning of the study: Table 5 lists napping features' Spearman correlations to functioning and health measures. Actigraphy napping time tends to be related to some functioning measures and self reported vigilance on the depression questionnaire result. In this population, actigraphy napping time differs between sleeping pill users and non users. Similar difference was observed for self-reported vigilance although the difference is not statistically significant (Fig. 2). Bed sensor napping time SD tends to be related to self reported sleep time.

End of the study: Functional tests had no statistically significant correlations with actigraphy napping time (except Crouch times correlation was almost statistically significant; P=0.92). Number of subjects in actigraphy napping time analyses was smaller (N=9 to 11) than in the beginning of the study due to missing actigraphy data or the performance tests. The bed sensor napping time or self-reported vigilance did not have statistically significant correlation to functional tests. For bed sensor and self-reported vigilance, the number of subjects in the analysis is between 8 and 12.

4. Discussion

4.1 Daily napping and activity behaviour features

Actigraph napping time tend to have significant connection to activity/exercise features. However, self-reported exercise was correlated positively with actigraph napping time although the correlation was small. This means that days which included more exercise tend to include more daytime napping. It has also been reported that older adults doing moderate to vigorous activities need to rest more during that day [6]. Meijer also found out that daily energy consumption was more related to lighter activities than high. Our findings are in line with these. However, two cases have strong negative correlation which conflicts the hypothesis and with seven days averaged data the connection disappeared. As mentioned earlier the study period was short and it might be normal not to see similar changes in individual level

than with the pooled data. In addition, the study period included exercise intervention which might affect the results. The self-reported exercise did not contain intensity information which should be included in the future studies.

The self-reported exercise and the steps have positive connection (0.257**, N=1153), the actigraph napping time and steps have negative connection (Table 1), but the self-reported exercise and the actigraph napping time have a small positive connection. We assume that steps can indicate light, moderate or even vigorous activities and it tells more about the total daily activity level, which would be the main reason for the strong connection between the average daily activity and the steps (0.616**, N=608). Again, we hypothesise that if an older person "exercising" they need rest, but if the day is just active without "exercising" they don't have to sleep/rest during the day. It would be important to study that if older adults are not doing "exercises" and still nap more than expected they could have some "health problems" e.g. degenerated functioning.

Average daily activity (-0.139**) and number of actigraphy data points during the day (-0.132**) have small negative correlation with self-reported exercise which might also indicate that the "exercises" have taken place out of range of the actigraphy's base station (covers basically the facility and close surroundings). To gain good understanding about the real daily activity behaviour we should take all the activity features into account..

Bed sensor napping time had connection only to average daily activity. This might indicate that the bed sensor based napping feature is not very strongly related to the amount of daily activity (behaviour). Some people tend to sleep during the day in the bed (where the bed sensor is located) and some people tend to sleep for example on a couch where the sensor is not present, which most likely is one reason for these two measures (actigraph and bed sensor) to differ. This tells that bed sensor is more suitable for night time than daytime sleep behaviour monitoring. However, there are two individuals who had strong positive correlation between self-reported exercise and bed sensor napping time. These subjects potentially tend to sleep in their bed during the day.

Wrist or hip worn actigraphic devices are more suitable for monitoring the daytime sleep/rest behaviour on the group level. Day time sleep also seems to be an important

Table 5

Spearman correlations coefficient between one month average and standard deviation of daily napping features and functioning/health (month in the beginning)

Napping features Health and functioning	Actigraphy napping time	Actigraphy napping time SD	Bed sensor napping time	Bed sensor napping time SD	Self-reported vigilance	Self-reported vigilance SD
Self rated health N	- 13	- 13	- 17	- 17	- 19	(almost -0.4) 19
Current exercise amount 	- 13	- 13	- 17	- 17	- 19	- 19
Sleep/ hours per night? 	- 13	- 13	- 17	-0.63** 17	- 19	- 19
Sleeping pills 	-0.62* 13	-0.742** 13			(almost 0.45) 19	- 19
MMSE N	- 10	- 10	- 16	- 16	- 16	- 16
GDS-15 N	- 13	- 13	- 19	- 19	-0.61** 19	- 19
ADL N	(almost 0.41) 13	- 13	- 19	- 19	- 19	almost (-0.44) 19
Right hand grip test N	- 13	- 13	- 19	- 19	- 19	- 19
Left hand grip test N	- 13	- 13	- 19	- 19	- 19	- 19
Balance test N	- 13	- 13	- 19	- 19	- 19	- 19
Crouch amount N	-0.82** 13	- 13	- 19	- 19	- 18	- 18
Chair stand 5 times N	(almost 0.43) 13	- 13	- 19	- 19	- 19	- 19
Step height N	(almost -0.39) 13	- 13	- 19	- 19	- 19	- 19
Walking speed 10 meters N	- 13	- 13	- 19	- 19	- 19	- 19

** Correlation is significant at the 0.01 level.

behavioural measure to evaluate the health status i.e. functioning according to our findings.

Steps and self-reported vigilance seem to have interesting correlation (Table 2). The problem with self-reported vigilance in the study was that it did not have variance on individual level which might have a downside in long term analysis. This might tell from the subjects' ability to assess longer term changes in their health. For example, if one felt two months ago the same asnow the health status could still have changed. This is why objective measures should also be used in long term monitoring of health.

On case-wise level, the connections between the features differed in some cases from the group level findings. This was expected as the study duration was only three months and no big health changes were observed. The couple of subjects who showed similar responses on individual level and in the pooled data could be interesting for a more thorough study to analyse what kind of reasons are behind the connections.

4.2 seven-day average data

The self-reported exercise did not have a statistically significant connection to other features. Steps had negative correlation to actigraphy napping time. This supports the daily data finding that the less you sleep during the day the more active you are when observing steps and general activity (average daily activity).

There is an almost significant correlation with the bed sensor napping time and the steps. However, this correlation is positive which is rather confusing when compared to the actigraphy napping time relationship with the steps. Moreover, the statistically significant correlation between self-reported vigilance and steps disappeared.

4.3 Functional capacity

The actigraphy napping time showed some interesting connections (in similar way as was hypothesized) to functioning tests. The actigraphy napping time values seem to be related to sleeping pill usage as well. Subjects reporting greater vigilance values did not use sleeping pills. One reason for this could be that if people sleep during the day they have difficulties with night time sleep and this is why they use sleeping pills. It could also be related to the fact that people with sleeping problems (sleeping pill users) are more passive during the day. Self-reported sleeping time (start level question) and bed sensor napping time SD connection can be related to subject's habits of either sleeping longer in the bed or going earlier to the bed. This might indicate that the time limit for day (from 10 am to 8 pm) is too long and it should be even narrowed. The bed sensor information could be used to adapt the daytime period positioning. Very interesting was also correlation between depression scale (GDS-15) and the self-reported vigilance. It would be of interest to study relationship between depression and objectively measured activity behaviour in longer term setup.

The functional tests should be combined to one common index and study if the objective measurements have a connection to that index as it might be more reliable measure of one's functioning compared to the separate tests. For example, when dividing the subject into two groups according to ADL questionnaire result (cut off = 20) the actigraphy napping time (month average) seems to be quite a good measure to distinguish users between different functioning groups (Figure 3, Spearman, P = 0.109, 0.465, 1: N=8, 2: N=5). Again the population is small and more data is needed to find out how these methods can help e.g. care personnel, clinicians or users.
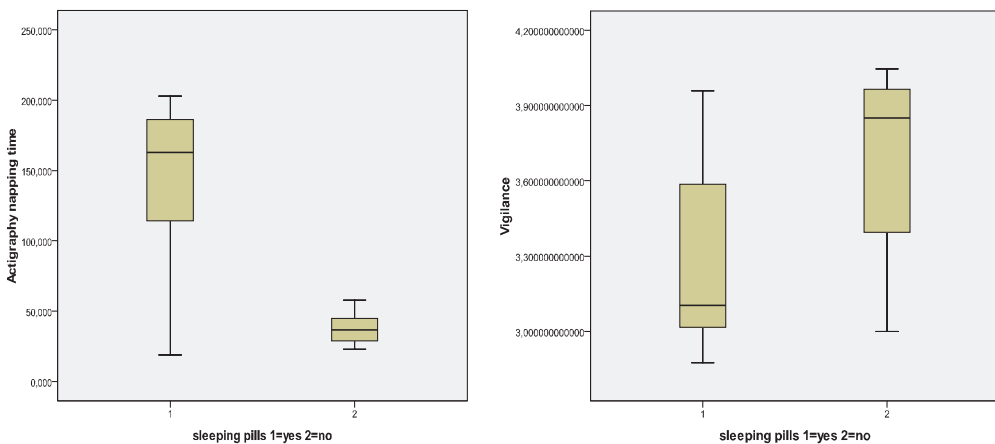

Figure 2. One month average actigraphy daily sleeping time and self-reported vigilance for sleeping pill users and non-users
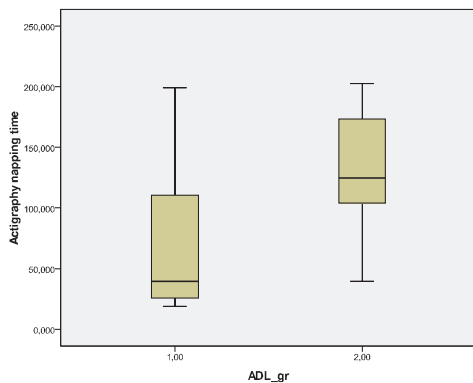
Figure 3. One month average of actigraphy daily napping time between ADL groups (cut off 20 points)

5. Conclusions

Actigraphy based napping time tends to be related to personal functional capacity and activity behaviour according to the data. Monitoring of this feature could be beneficial for indicating health problems or even detecting changes in the health status.

Different activity features (in our case: steps, self-reported exercise and average daily actigraphy activity) should all be considered to form a holistic personal activity profile as the features tend to describe somewhat different behaviour according to our findings.

Self-reported vigilance had the downside of missing variance on individual level, and implies that objective measures are needed for revealing daily alertness status.

It would be of interest to study the connection between depression and objectively measured activity behaviour in a long term study setup as self reported vigilance was found to have negative correlation with Geriatric Depression Scale (GDC-15).

Acknowledgement

We would like to thank the care facility personnel for their contributions.

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Estimating older people's physical functioning with automated health monitoring technologies at home: Feature correlations and multivariate analysis

PUBLICATION V

Wearable monitoring of physical functioning and disability changes, circadian rhythms and sleep patterns in nursing home residents

IEEE Journal of Biomedical and Health Informatics, 20 (3), art. no. 7081384, pp. 856-864.

Wearable Monitoring of Physical Functioning and Disability Changes, Circadian Rhythms and Sleep Patterns in Nursing Home Residents

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Abstract—Sleep problems and disrupted circadian rhythms are common among older adults and may be associated with several health issues and physical functioning status. Wearable continuous monitoring of physical activity enables unobtrusive monitoring of circadian activity and sleep patterns. The objective of this retrospective study was to analyze whether physical functioning status (Activities of Daily Living assessment of Resident Assessment Instrument) is associated with diurnal activity rhythm and sleep patterns measured with wearable activity sensor in nursing home residents during their normal daily life. Continuous activity data were collected by the wearable sensor from 16 nursing home residents (average age of 90.7 years, seven demented subjects, one female) in their daily life over several months (12–18 months). The subjects' physical activity and sleep were quantified by several parameters from the activity data. In the cross-sectional analysis, physical functioning status was associated with the strength (RHO = 0.78, $P < 0.05$) and the stability (RHO = 0.72, $P < 0.05$) of the activity rhythm when the level of dementia was not controlled. In the longitudinal analysis (12–18 months), at an individual level the activity rhythm indices and activity level had the strongest correlations with changes in physical functioning but the associations were to some extent individual. In these long-term case recordings, decrease in the physical functioning was most strongly associated with decreasing levels of activity, stability, and strength of the activity rhythm, and with increasing fragmentation of rhythm and daytime passivity. Daily wearable monitoring of physical activity may hence reveal information about functioning state and health of older adults. However, since the changes in activity patterns implying changes in physical functioning status may not be consistent between the individuals, a multivariate approach is recommended for monitoring of these changes by continuous physical activity measurement.

Index Terms—Activities of daily living, ambulatory monitoring, dementia, long-term, physical activity.

I. INTRODUCTION

SLEEP problems are common among older adults and are typically associated with health issues rather that aging itself [1]. Poor sleep increases risk for decreased physical functioning, memory problems, increased risk of fall and mortality

[1]. Sleep has a strong connection with circadian rhythms which are prevalent to changes in aging [1], [2]. Circadian rhythms are as well present in most of the human physiological processes and are controlled by a brain region named suprachiasmatic nucleus (SCN) which is synchronized and strengthened by external inputs (zeitgebers) such as bright light and physical activity. Typically, aging has been associated with circadian rhythm phase advance, damping of the rhythm's amplitude, and internal desynchronization of different rhythms [2]–[4]. In addition to aging, illness and degenerated functioning can harm an individual's ability to compensate for irregularity of zeitgebers and, thus, can predispose to circadian rhythm disorders [5]. For example, a nursing home environment can disrupt diurnal activity rhythms and sleep/wake patterns through limited exposure to sunlight, long periods spent in bed, physical inactivity, and a disturbing night-time environment [6].

Polysomnography (PSG) is the golden standard in sleep assessment but it is typically impractical during everyday life since it requires continuous monitoring of multiple physiological measures [7]. Actigraphy (measuring physical activity for extended periods, typically worn on wrist) is a common method for studying diurnal activity rhythms and alternative for PSG in assessment of sleep/wake patterns, especially in naturalistic conditions [8], [9]. Actigraphy is found to be a valid method for estimating bedtime, wake-up time, mid-sleep time, and activity rhythm's acrophase (timing of the 24 h rhythm) when compared with urinary circadian rhythm measures in young and older adults [8]. However, actigraphy is not necessary an accurate estimate of SCN output owing to the masking of environmental pressures [8].

Sleep duration and sleep continuity are typical sleep measures inferred from actigraphy. However, since actigraphy is a measure of activity/passivity, it can falsely quantify sleep when the subject is, for example, simply lying still [7]. Actigraphy also cannot be used for estimating some PSG-based measures such as sleep architecture. For nursing home environment, actigraphy is reported to be suitable for characterizing and monitoring sleep and activity rhythm patterns, and for documenting treatment outcomes [10]. Actigraphy measured changes in activity rhythm and sleep/wake pattern have been associated with degenerated health and functioning among nursing home or assisted living facility (ALF) residents. [6], [11]–[15].

Typically, lower activity rhythm stability and amplitude, and higher activity rhythm fragmentation were an indication of disability and degenerated functioning [13], [15]. Actigraph-measured sleep efficiency was worse and daytime nap length

was longer for ALF residents than for community dwelling older adults. [16] However, there are some differences in the exact pattern of these reported associations, and it is not well known whether changes in functioning state in nursing home populations are also related to changes in actigraphic recordings, since most of the studies report results with cross-sectional data.

In the present retrospective study, we examined whether circadian physical activity and sleep/wake patterns as measured by wearable wrist-worn activity sensor were associated with the functioning assessments [Resident Assessment Instrument (RAI) components] of nursing home residents in long-term monitoring (several months). Changes in physical functioning status (Activities of Daily Living) are in focus. We have studied the association with cross-sectional and individual, longitudinal analysis between actigraphic measures and functioning assessments.

II. MATERIALS AND METHODS

A. Subjects

Study material consisted of health record data and long-term wearable wrist-worn activity sensor recordings of a medium-sized nursing home's residents. Activity data from 23 subjects aged 90.9 ± 4.2 years (mean $\pm$ standard deviation) were initially included in the study data collection (seven demented, one female).

Data were anonymized before analysis. The study was a retrospective database study and was accepted by a local ethical committee and the facility's review board.

B. Health Record Data

The RAI [17] is collected in the facility every six months. RAI is widely used instrument in nursing home setting globally. The results of the instrument are used for assessing care and resource needs in the facility. Four indices describing functional capacity of the residents were included in the analysis from RAI.

1) *Physical Functioning (Disabilities):* Activities of the Daily Living (ADL) scale ranged from zero (no impairment) to six (total dependence). Higher level activity disabilities such as dressing were assigned with a lower score whereas loss in basic activity such as eating gained a higher score.

2) *Cognitive Functioning:* "The cognitive performance scale (CPS) combines information on memory impairment, level of consciousness, and executive function, with scores ranging from zero (intact) to six (very severe impairment). The CPS has been shown to be highly correlated with the Mini Mental State Examination, which is very commonly utilized instrument in these settings" [17].

3) *Pain:* The scale ranged from zero (no pain) to three (daily severe pain) and has shown to be strongly connected to the visual analogue scale-based pain measure.

4) *Mental Functioning:* A seven item depression scale (DRS). The score ranged between zero (no mood symptoms) and 14 (all mood symptoms during the last three days).

In addition to the RAI components, background information from health records (e.g., age, gender, diagnosis, and medication) was included in the analysis. Baseline RAI scores of the subjects ($n = 23$) were 1.5 ± 2.0 for ADL, 0.9 ± 0.9 for Pain and 1.9 ± 2.4 for DRS (mean $\pm$ standard deviation). The RAI scores are not normally distributed.

C. Equipment

The device collecting the user's activity data is a social alarm system (i.e., panic button on a wrist-worn device, Vivago Inc., Espoo, Finland) with an integrated activity sensor (named telemetric actigraphy hereon). The sensing modality in the device detects micro and macro movement of the wrist, based on which an activity epoch value on arbitrary units is defined for each minute (sampling frequency not configurable). In addition, the device monitors wearing adherence (detection whether the device is on the wrist) based on skin conductivity measurement [18].

The system makes a minute-to-minute sleep/wake classification with a level of accuracy similar to traditional actigraphy when validated against PSG. In a validation study including older people at day centers [19] the agreement with PSG sleep/wake classification was 77% for the telemetric actigraphy and 75–77% for traditional actigraphy (Actiwatch, Cambridge Neurotechnology in 2003). In the validation study, 30 s PSG samples were transformed to "the epochs of 1 min by rescoring "wake" whenever both sleep and wake states were present within the epoch" [19]. Telemetric actigraphy were more sensitive for low-intensity activities, whereas traditional actigraphs have better dynamics in high-intensity activities [19]. Furthermore, telemetric actigraphy was found to be a sensitive method of detecting changes in the health status of older subjects, especially when it was compared to the wearers own history data [11]. In the present study, minute-to-minute activity data were stored automatically on the institute's server computer from which it was extracted and anonymized before analysis.

D. Actigraphic Data Analysis Procedures

A number of methodologies exist for deriving the activity levels, activity rhythm, and sleep/wake patterns from the actigraphic time series data (minute epochs). For this study, we selected frequently utilized and studied methods for actigraphy data analysis that have been used for reporting results in similar populations. Two weeks long activity time series data have been recommended for the analysis procedures [20].

1) Diurnal activity rhythms have been modeled with sinusoidal waveforms. In this procedure, a single cosinor function model with 24 h period is fitted to actigraphic time series data via the least-squares method. The procedure results estimates for mesor (MESOR, time series mean representing the mean activity level), amplitude (AMPL, difference between mesor and peak of the fitted waveform), and acrophase (PHASE, timing of the waveform peak) [21], [22].

2) Three indices of nonparametric methods for describing characteristics of hourly activity time series—interdaily

stability (IS), intradaily variability (IV), and relative amplitude (RA)—were inferred from the actigraphic data for the analysis. The procedures utilize epochs consisting of the number of active minutes in each hour instead of the minute samples [12]. In this study, minute-epochs with value of four or above were classified as active after which the hour epochs were created. The threshold selection was based on a concurrent validation analysis between the traditional actigraph (Actiwatch, Cambridge Neurotechnology in 2003) and the telemetric actigraph (data not shown).

IS describes the stability between the days, implying stable zeitgebers. It is the 24 h value of chi-square periodogram

$$IS = \frac{n \sum_{h=1}^{p} (x_h - x)^2}{p \sum_{i=1}^{n} (x_i - x)^2} \tag{1}$$

where n is total number of hour epochs, p is number of data per day (24 in this case), x_h is hourly mean over all hour epochs (for example, between 16:00 and 17:00 for all the days), x_i is individual hourly epoch, and x is mean of all hourly epochs.

IS is reported to vary between zero for Gaussian noise and one for perfect match between the days that is the average hourly epochs and the all hourly epochs have equal variance [12].

IV quantifies the fragmentation of the rhythm and activity. It is the ratio between the variance of the consecutive hourly epochs and overall variance [12]

$$IV = \frac{n \sum_{i=2}^{n} (x_i - x_{i-1})^2}{(n-1) \sum_{i=1}^{n} (x_i - x)^2}. \tag{2}$$

IV gets values near zero for perfect sine wave and about two for Gaussian noise that is the more fragmented activity rhythm the larger values IV gets. For example high IV (>1) was reported to indicate of daytime naps and/or nighttime arousals [13].

RA is the normalized ratio between the most active 10 h and the least active 5-h activity periods

$$RA = \frac{M10 - L5}{M10 + L5}. \tag{3}$$

3) A circadian rhythm strength (CRS) variable was calculated by dividing average night-time activity (11 PM–5 AM) by the average activity of the previous day (8 AM–8 PM) for each 24-h period [23], [24]. Averages of these values from during the selected actigraphy periods have been used in the analysis.
4) Total sleep time (TST) and daytime sleep/passivity amount (NAP) are based on the minute-to-minute sleep/wake classifications provided by the telemetric actigraphy system. TST was calculated as the sum of sleep classifications during the night-time and NAP during

TABLE I
FREQUENCIES OF RAI'S FUNCTIONING ASSESSMENT SCALE'S SCORES IN CROSS-SECTIONAL ANALYSIS (N OF SAMPLES = 31, N OF SUBJECTS = 16)

Score	Activities of Daily Living	Pain scale	Depression Rating Scale	Cognitive Performance scale
0	7	14	14	13
1	4	9	7	4
2	7	8	1	0
3	2	0	4	1
4	2	-	4	0
5	7	-	0	11
6	2	-	1	2

the daytime. Daytime period was defined as between 9 AM and 9 PM as in [11], and night-time between 9 PM and 8 AM. Especially, the nigh-time period selection is based on the institutions schedule, which, according to visual observations from the actigraphy data, appeared to activate residents between about 7 AM and 8 PM. Typically TST is inferred utilizing simultaneously sleep diary and actigraphic data. However, this is not feasible in long-term care settings. In addition, the number of awakenings (AWAKN) was assessed by detecting transitions from sleep to awake during the night-time.

E. Statistical Analysis

Two distinctive analyses were made to study how changes in physical functioning can be visible in diurnal activity rhythms and sleep patterns measured with telemetric actigraphy.

F. Cross-Sectional Analysis

For analyzing the association at the group level, we selected actigraphic data of at least seven days (target was 14 days) that were close to the RAI assessment to which the data analysis procedures were applied [20]. Data from 16 residents (six demented subjects, one female) aged 90.9 ± 4.2 years (mean ± standard deviation) met the inclusion criteria (at least seven days of continuous actigraphy data close to functioning assessment, with $<20\%$ missing data) and were included for the further analysis. Baseline RAI scores for the selected subjects were 1.4 ± 1.9 for ADL, 0.9 ± 0.9 for Pain, and 1.8 ± 2.5 for DRS (mean ± standard deviation). In total, there were 31 data samples from these 16 subjects. Frequencies of the RAI scores are given in Table I.

Time periods when the actigraph was off the wrist or out of the base station range were considered missing data. The average actigraphy sample length was 12.0 days with 5.1% missing data. Nights with more than 30 min of missing data were removed from the analysis. Days with more than 20% of missing data were removed from the analysis. These selections mostly ignored data periods with larger amount of missing data.

For studying the association between actigraphy parameters and RAI scores, a weighted rank order correlation was calculated. Weighting by the number of observations can be used when there is different number of observations for each subject [25]. In the analysis, subject means are included in the analysis instead of the repeated measures [26]. In addition, partial rank

TABLE II
WEIGHTED AND PARTIAL RANK ORDER CORRELATION COEFFICIENT (WEIGTED/RANK) CONTROLLED FOR CPS BETWEEN FUNCTIONING STATUS
ESTIMATES (RAI) AND ACTIGRAPHIC PARAMETERS (n OF SAMPLES $= 31$, n OF SUBJECTS $= 16$)

RAI measure Actigraphy measure	RAI Activities of Daily Living (ADL)	RAI Pain	RAI Depression Rating Scale	RAI ADL smaller than or equal to median ($N = 9$)	RAI ADL larger than median ($N = 7$)
Cosinor mesor (MESOR [epoch])	−0.20/−0.26	0.38/.43	0.45/0.48	10.3(5.7)	11.3(10.6)
Cosinor amplitude (AMPL [epoch]))	−0.35/−0.21	0.45/0.48	0.27/0.39	12.4(7.4)	9.2(8.6)
Cosinor acrophase (PHASE [time])	0.24/−0.28	−0.12/0.08	−0.11/−0.24	15:56 (1:27)	16:15 (1:45)
IS	**−0.70***/−0.20	−0.04/−0.29	−0.54/−0.40	0.57(0.19)	0.36(0.15)
IV	0.60/0.45	−0.43/−0.37	0.22/0.11	0.63(0.23)	0.83(0.19)
RA [hourly epoch ratio]	−0.58/−0.10	−0.11/−0.44	**−0.67**†/**−0.60**	0.55(0.18)	0.35(0.17)
Circadian rhythm strength (CRS [epoch ratio])	**0.78***/0.59	−0.08/−0.02	0.37/0.13	0.30(0.17)	0.57(0.22)
Daytime sleep/passive amount (NAP [minutes])	0.29/0.38	−0.45/−0.56	−0.28/−0.42	98 (90)	111 (83)
Total sleep time (TST [minutes])	−0.13/0.38	−0.25/−0.60	−0.50/−0.53	550(104)	490(177)
Number of awakenings (AWEKN)	−0.17/0.29	0.11/−0.26	−0.45/−0.49	1.7 (0.9)	2.1(1.5)

*$P < 0.05$ for weighted correlation coefficient, † $P < 0.1$ for weighted correlation coefficient.
Average (standard deviation) values of the actigraphy parameters are given for subjects grouped according to median of the functioning status estimate (RAI ADL).

order correlation to control for the impact of dementia was analyzed. Dementia patients typically can have altered sleep/wake patterns. Subject means were included for the partial correlation analysis.

Bonferroni correction was applied to compensate for multiple correlations [27]. The Spearman's correlation coefficients for critical values 0.1, 0.05, and 0.01 are, respectively 0.65, 0.69, and 0.76 for sample size of 16.

G. Longitudinal Analysis

Longitudinal case analyses were performed for those subjects who had actigraphic data available for at least one year or during at least three RAI ADL assessments. In total, five cases fulfilled the inclusion criteria for the studying of longitudinal associations. The average actigraphic monitoring period was 449 days (range 320–489). For the case analysis, we extracted the actigraphy parameters from 14-day long data samples with seven-day increments resulting in time series data. For each 14-day data point, 75% of actigraphic data were required for inclusion in the time series data. The same exclusion criteria with missing data for each day were used in longitudinal analysis as in the cross-sectional analysis. RAI ADL scores were resampled to represent similar time series data. These ADL data points are linear estimates between the RAI assessments. Spearman rank order correlations between the time series data were calculated for the subjects who had changes in RAI ADL. Rank order correlation was selected since the resampled RAI ADL was not normally distributed. The aim of this analysis was to reveal how changes in actigraphy and functioning status are associated at the individual level in the long-term recording.

III. RESULTS

A. Cross-Sectional Analysis

Table II presents weighted and partial correlation coefficients between actigraphic parameters and functional status estimates,

and absolute values of the actigraphy parameters for subjects divided according to median value of RAI ADL. Each subject's baseline RAI assessment moment were selected for absolute value calculation.

B. Longitudinal Analysis

We selected three cases (out of five) to visualize how the changes in functioning can reflect in the activity behaviors quantified with actigraphic data. Table III provides a summary of the case analysis, including the correlation coefficients for all the five cases. In addition, there were three cases in the dataset with long-term good quality actigraphic data which did not have changes in RAI ADL during the study, so correlations for these cases could not be reported.

Fig. 1 presents data for Case #8 (female, 89 years, nondemented, sleep-medicine user), whose actigraphy parameters reacted in the predicted way (that is agrees with literature and the group-level findings) when compared with the deterioration of physical functioning according to ADL. PHASE and TST did not correlate with the ADL trend. AMPL, IS, IV, RA, and CRS follow the ADL trend. Double plotted actogram visualizes how the activity rhythm becomes more disturbed and less intensive toward the end of the recording.

Fig. 2 shows Case #15 with deteriorating functioning (male 101 years, nondemented, no sleep medicine). AMPL IS and CRS follow the changes in functioning. Similar to Case #8, TST and PHASE are not significantly correlated with the ADL trend. Double plotted actogram shows that the main changes in the activity behavior are decreasing trend of the activity level, and later morning activity. These changes are well visible in the parameter values in the end of the recording.

Fig. 3 presents data of Case #19 (male, 88 years, vascular dementia, sleep-medicine user). The actigraphic parameters do not agree with expectation from the literature or group-level findings. For example, IS and IV indicate an improving condition, although the ADL score worsens during the monitoring

TABLE III
CASE ANALYSIS FOR ASSOCIATIONS BETWEEN PHYSICAL FUNCTIONING ASSESSMENT AND ACTIGRAPHY CHANGES

Actigraphy measure Case	Length [days]	AMPL [RHO]	RA [RHO]	IS [RHO]	IV [RHO]	CRS [RHO]	NAP [RHO]	PHASE [RHO]	TST [RHO]	AWAKN [RHO]	ADL [scale]
#8, 89 years, nondemented	489	−0.62	−0.62	−0.64	0.69	0.57	0.70			0.54	(5)-1–2-(5)
#9, 88 years, demented	320	−0.62		−0.64			0.51		0.72	−0.57	5–6–6
#15, 101 years, nondemented	478	−0.41	−0.34	−0.46	0.34	0.53	0.26			−0.38	(2)-2–5–5
#19, 88 years, demented	487		0.55	0.54	−0.44	−0.38	0.29	−0.48			(1)-1–3-(3)
#27, 91 years, nondemented	470			−0.52	0.74	0.57	0.53		0.31		(0)-2–0

Abbreviations: AMPL, cosinor amplitude; RA, relative amplitude; IS, interdaily stability; IV, intradaily variability; CRS, circadian rhythm strength; NAP, daytime sleep; PHASE, cosinor acrophase; TST, total sleep time; ADL, activity of daily living score (RAI); length, length of actigraphy recording.
Spearman rank order correlations [RHO] are given between actigraphic parameters and RAIs's activities of daily living scale (RAI ADL). Only significant correlations ($P < 0.05$) are shown. RAI ADL scores are given in chronological order. RAI ADL Assessments outside the actigraphy recording are presented in parenthesis.
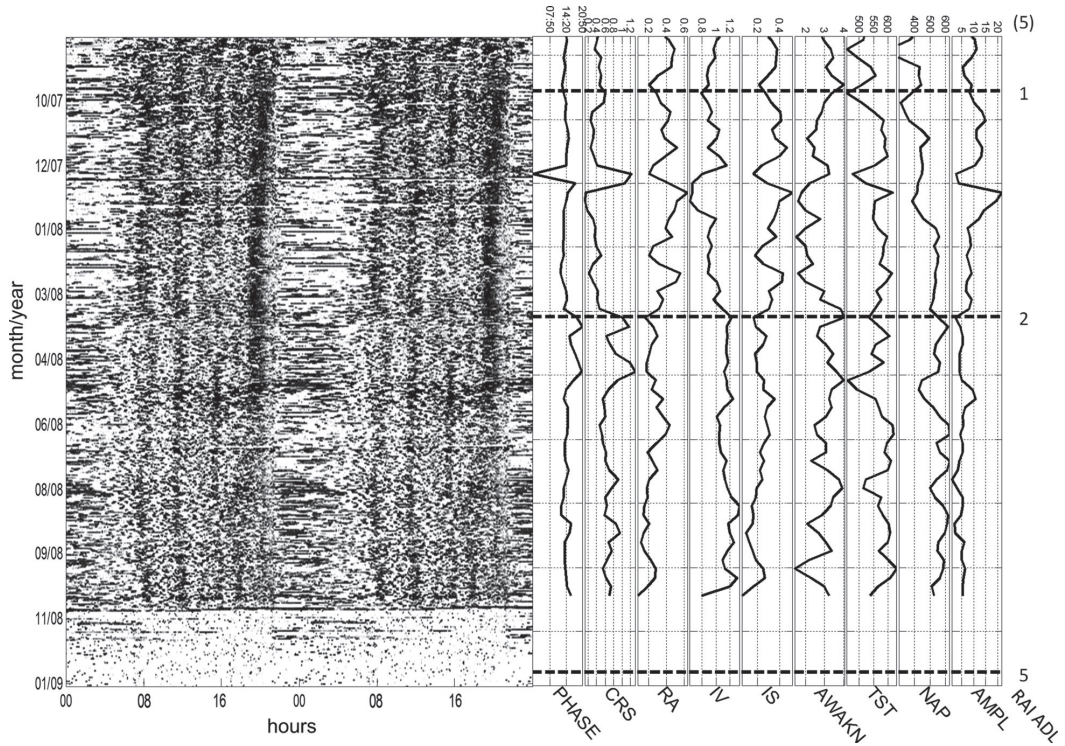

Fig. 1.   Case #8: Actigraphy parameters and double plotted actogram of 489-day long recording, and Resident Assessment Instrument Activities of Daily Living scores (RAI ADL, value before the actigraphy recording period is given in parenthesis) and times (dashed vertical line). Cosinor amplitude (AMPL [epoch]), daytime sleep (NAP [minutes]), TST (minutes), number of awakenings (AWAKN [n]), IS, IV, RA, circadian rhythm strength (CRS), cosinor acrophase (PHASE [time])

period. According to the double plotted actogram, there are no major changes in activity behavior during the recording. Slight decrease in IV can be related to the more evenly distributed activity behavior during the daytime in the later phase of the recording.

IV. DISCUSSION

The objective of this study was to determine whether changes in functioning are reflected in actigraphic recordings of activity rhythm and sleep patterns in nursing home residents. In a group-
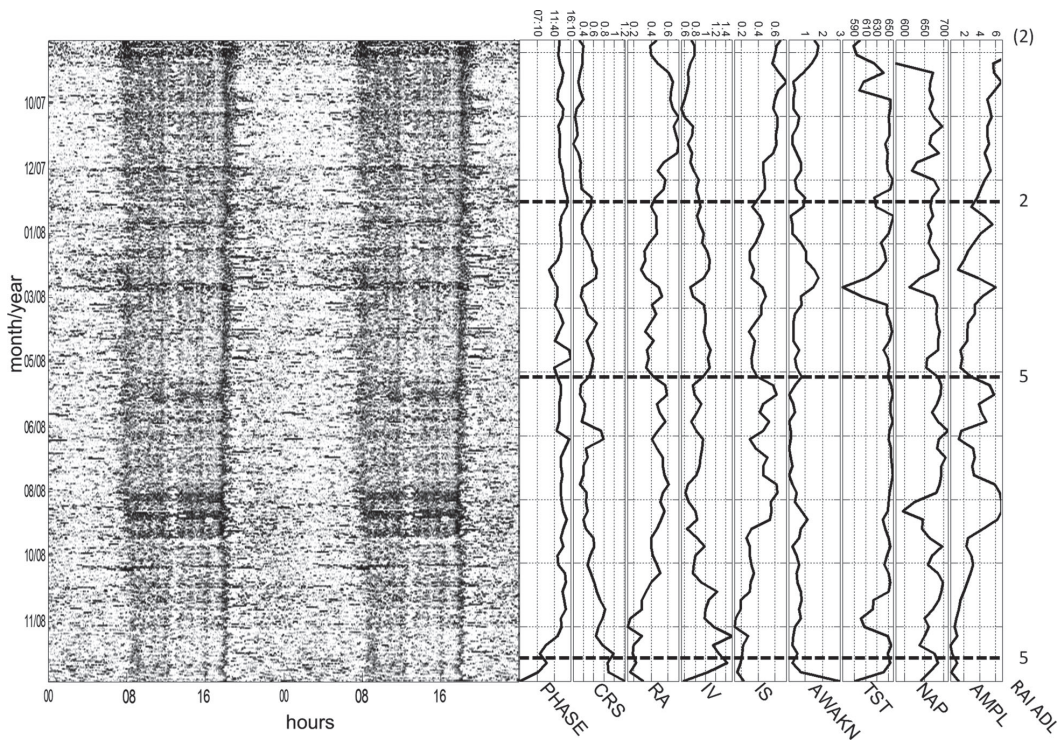
Fig. 2.   Case #15: Actigraphy parameters and double plotted actogram of 489-day long recording, and Resident Assessment Instrument Activities of Daily Living scores (RAI ADL, value before the actigraphy recording period is given in parenthesis) and times (dashed vertical line). See abbreviations from Fig. 1.

level analysis, we found that actigraphic-measured strength of activity rhythm was associated with the physical functioning status. In addition, activity rhythm stability had strong correlation with physical functioning but the association weakened when controlled with dementia suggesting that the association might be related to disrupted sleep-wake cycle in dementia. These findings are generally in agreement with previous reports in the literature [11]–[13], [15]. We did not encounter the commonly reported u-shape connection between sleep time and physical functioning for community-dwelling older adults [28], [29].

In addition to correlation analysis, we reported absolute values of the actigraphic variables for subjects divided into two groups by the median score of physical functioning assessment. In related literature, there exists some controversy in how to interpret these absolute values, especially the activity rhythm parameters. In large epidemiological study including community dwelling older females, the later acrophase (later than 16:30) was found to associate with impaired functioning (instrumental ADL) [30]. However, the acrophase was not associated with dementia or functioning status in study with nursing home residents [11], with which our findings agree. The acrophase of the actigraph in our population in average is later (close to 16:00) compared to what was reported in article [11] (close to 12:00).

The changes in physical functioning status were not strongly reflected in the activity acrophase in case analysis either.

IS (stability of the rhythm) has reported to be close to 0.6 for healthy older people on average [31]. Decreasing trend (toward dissimilarity between days) tends to indicate worsening health condition and functioning for demented subjects [12], [15], [32]. Reported IS values were from 0.50 to 0.65 on average in these studies. In our data when dividing subject into better and worse functioning groups, the average IS values were 0.57 and 0.36, respectively. Although the correlation between RAI ADL and IS weakened when controlled with severity of dementia, the absolute values in these two groups of different functioning are as expected according to the literature. In case analysis, IS values decreased close to 0.2 along the deteriorating functioning for Case #8 and Case #15.

IV tended to be age-dependent with the average value of 1.2 for healthy older people [31], but its association with health status changes has not been systematic [12], [32]. On the group level, a negative association has been found between IV and functioning, lower IV indicating better functioning among demented nursing home residents (0.74 on average) [15]. We found strong, although not significant, correlation between IV and physical functioning similar to article [15]. The absolute values which we encountered support those in the literature; 0.63 for
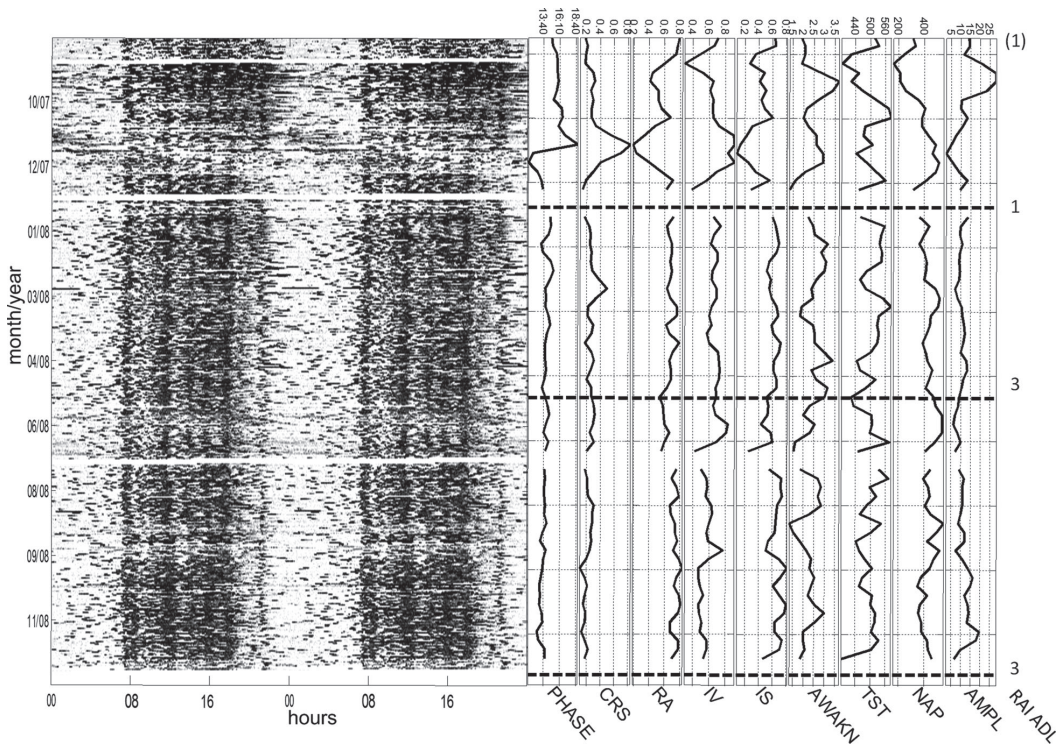
Fig. 3.   Case #19: Actigraphy parameters and double plotted actogram of 489-day long recording, and Resident Assessment Instrument Activities of Daily Living scores (RAI ADL, value before the actigraphy recording period is given in parenthesis) and times (dashed vertical line). See abbreviations from Fig. 1.

subjects with better functioning and 0.83 for subject with worse. For Case #8 and Case #15, IV values changed approximately from 0.8 to 1.2 during the recording.

RA has been reported to decrease with worsening health status, and vice versa [12], [15], [32]. The values were on average 0.6 or 0.7 [12], [15]. Our data showed a similar trend between RA and functioning with the literature but absolute values are now slightly lower: 0.55 on average for better functioning subjects and 0.35 for worse functioning subjects. The case analysis demonstrated as well changes of similar size.

CRS, referring to the relationship between daytime and night time activity, was found to get values of 0.3 on average for nondemented nursing home residents and 0.5 for demented [11]. CRS has also showed sensitivity to detect health changes in long-term monitoring [24]. In our data values, 0.3 on average were associated with better functioning half, and 0.57 with worse functioning.

Our analyses did not show a statistically significant association between pain and actigraphic parameters. Mormont *et al.* [33] reported that higher bed time activity correlated with increased pain for cancer patients; however, actigraphy-measured daytime activity level or stability of the rhythm (24 h autocorrelation) lacked an association with pain in the study. Lunde *et al.* [34] reported that for older adults, sleep efficiency was associated with pain ($P = 0.055$): the chronic pain group had

lower sleep efficiency in their study. Although we did not encounter this type of association, we note that disturbances in sleep-wake cycle due to dementia can have affected on the results and with larger sample size subpopulation analysis is encouraged.

The RAI DRS was correlated with the RA implying that the lower normalized ratio between low activity and high activity periods signal possible depressive symptoms. This finding with depression indices are in agreement with previous reports [15], [16], although some differences exist. For example IV and especially IS had stronger association with depressive symptoms than RA in demented older females [15]. For ALF residents, depression level and change in the level were associated with continuity of the sleep [16].

The case analysis showed that physical functioning changes are correlated with the actigraphic parameters as expected in most of the cases; however, the associations were, to some extent, individual. For Case #19, activity rhythm parameter changes compared with functioning changes differed from the majority. Since the change in health might produce somewhat individual activity behavior pattern changes, parallel analysis of multiple parameters would be beneficial. Timing of the rhythm (acrophase) was not associated with functioning in the case analyses or in the group level analysis. In general, the parameters depicting activity rhythm tended to be more sensitive than sleep

parameters for detecting health changes according to the longitudinal analysis. We note though that the telemetric actigraphy is reported to be less sensitive for detecting activities with higher intensities, and findings that are based on the count measures, such as IS and IV (fragmentation), might be more generalizable. Although the analysis procedures are important when comparing the results to reference values or subject's own history data, we suggest that observing the original data for example via double plotted actogram, can help to understand the origin of the possible problem.

Our study population consisted of demented and nondemented residents, which may have disturbed the group results. Thus, we recommend separate analyses for demented and nondemented subjects with a larger sample. Moreover, actigraphic evaluation of demented persons with different severity of dementia would be valuable. For example, Alzheimer patients with behavioral and psychological symptoms (such as apathy and aggression) had activity patterns that were different from patients without these symptoms [35], [36]. Furthermore, the cognition status was associated with activity rhythm stability in demented subjects [15].

The variance of the time series data in some parameters was relatively high according to visual observations, which should be considered when interpreting the measurement results, especially point measures. We did not analyze whether there existed seasonal variation in the actigraphic parameters, which can be present in circadian rhythm markers and has been encountered for community dwelling older adults in activity and sleep behaviors [37]–[39].

The strength of the present study was in the long measurement period, which made it possible to observe changes in the consecutive data. The long measurement was made possible by the device, which was mainly used as an alarming device, whereas actigraphic use was a secondary feature. However, we note weaknesses in the analysis: the lack of a sleep log and of controlling factors such as interventions due to the retrospective nature of the analysis, and small sample size in the cross-sectional analysis. We note that the telemetric actigraphy's minute-to-minute activity value is proprietary, which limits the generalizability of the results of certain parameters such as the activity amplitude. However, there are also differences in outputs between the traditional actigraphs [8], and it is unlikely that the results would differ significantly if a traditional actigraph had been used (e.g., based on zero crossing and time above threshold counts). It should also be noted that some of the selected actigraphic parameters are related and with larger data libraries factorial analysis is encouraged.

V. CONCLUSION

The results suggest that long-term wearable physical activity monitoring may be useful for detecting trend changes in several activity behaviors reflecting functioning and health changes in nursing home environment. Encountered changes in actigraphic indices in case analysis were in similar magnitude than expected according to findings reported in literature at cross-sectional studies. The activity rhythm and activity level indices were more sensitive to indicate physical functioning changes than the sleep indices. When using actigraphy in screening and outcome monitoring, multivariate and personalized analysis methods exploiting multiple actigraphy parameters might be needed and should be studied further. Our results suggest that degeneration and break-down of circadian rhythm due memory disorders has to be taken into account when interpreting long-term nursing home residents' actigraphic recordings.

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Association between continuous wearable activity monitoring and self-reported functioning in assisted living facility and nursing home residents

ORIGINAL RESEARCH

ASSOCIATION BETWEEN CONTINUOUS WEARABLE ACTIVITY MONITORING AND SELF-REPORTED FUNCTIONING IN ASSISTED LIVING FACILITY AND NURSING HOME RESIDENTS

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Abstract: *Background:* Physical functioning is a key factor in independent living, and its preclinical state assessment and monitoring during the subject's normal life would be beneficial. *Objectives:* The aim of the study is to analyse associations between ambulatory measured physical activity behaviour and sleep patterns (wrist actigraphy) and self-reported difficulties in performing activities of daily living. *Participants, setting and design:* 36 residents in assisted living facilities and nursing homes (average age=80.4±9.0 years) without dementia in free living conditions participated. Actigraphic monitoring is integrated with the facilities' social alarm system. *Measurements:* Indices on activity level, activity rhythm, sleep pattern and external stimuli response of sleep-wake behaviours were extracted from the actigraph data and correlated (Spearman rank-order correlation) with activities of daily living measures. Bonferroni correction for multiple comparisons was applied. *Results:* Activity level (ϱ=-0.49, p<0.05) and night-time activity variance (ϱ=-0.69, p<0.01) had correlation with the activities of daily living scores. The similarity of subject-wise activity pattern to facility common activities had a trend with activities of daily living (ϱ=-0.44, p<0.1). In longitudinal case analysis, sleep and activity patterns were found to be associated with local weather variables. *Conclusions:* Activity patterns as measured by actigraphy may provide objective information on older people's behaviour related to functioning state and its changes in nursing home and assisted living facility settings. However, variance between individuals was large in this dataset which decreases the reliability of the results. Furthermore, external stimuli such as weather and facility-related activities can affect subjects' activity and sleep behaviour and should be considered in the related studies as well.

Key words: Activities of daily living, sleep, circadian rhythm, actigraphy, nursing home, assisted living.

Introduction

Physical functioning, describing a person's ability to manage day-to-day activities independently or assisted, varies at different stages of health, life situations, and age (1). In addition to the physical capabilities, functioning is affected by environmental and personal factors (2). If functioning status is maintained at a higher level than minimally required by the surroundings, it can delay and shorten the period of aid needed and thus could lengthen the time of independence. Hence, assessment and follow-up of the preclinical state of functioning (before disabilities occur) for a person potentially at risk (typically an older adult) should be given focus and studied further.

Different low-cost technologies, such as pedometers, fitness trackers, or even novel computer controllers, enable the recording of a subject's activity behaviour during normal life, which further could provide means to monitor the user's health or functioning status. These technologies could "be validated against a battery of currently used—and widely accepted—techniques and indices" (3) such as physical functioning estimates.

The actigraphy, being one example of such a technology, is a widely used modality measuring activity and rest behaviour during daily life. The actigraph unit is typically worn on the wrist, which also makes it reasonably unobtrusive to wear for extended periods. It is typically used in sleep research and sleep medicine to infer user's activity levels, circadian rhythm parameters, and sleep/wake patterns (4). There are recommendations that suggest the usefulness of actigraphy in sleep and circadian rhythm monitoring among older people, and especially among nursing home residents (4, 5). Actigraphy is also reported to provide meaningful information on the behaviour patterns associated with the functioning state of older adults (6-9). Thus it could be a valuable instrument to assess and monitor the preclinical risk of deteriorated functioning and disabilities in this older adult population.

Some studies already exist on the topic. For example changes in functioning and health have been associated with changes in sleep patterns. Short and long sleepers are more likely to have functional limitations among community-dwelling older people (7, 10). Longer daytime naps and disrupted sleep have also been associated with functional limitations (11).

Human biological daily rhythms (circadian rhythms) are stimulated by environmental factors such as bright light, social activity, food, and physical exercise (12). It has been suggested that the ability to maintain a regular endogenous

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rhythm is attenuated as we age (13), and monitoring of these rhythms might as well give indication of the functioning status changes.

For example later diurnal activity timing and activity level were associated with impaired functioning (instrumental activities of daily living; IADL) among community-dwelling older adults (8). Dissimilarity between the daily activity patterns tends to indicate a worsening condition and vice versa (14, 15). A similar trend was found for women with dementia, when compared with functioning and health instruments' scores (9). Also more fragmented daily activity patterns were associated with worse functioning status.

Since functioning and ageing might influence on an older person's ability to respond to the different environmental cues and their disruptions (13), measures on these stimulus-response associations could as well be used when evaluating the person's functioning status. Associations have been encountered between physical activity and weather conditions such as daily temperature, day length, and sunshine amount for community-dwelling older adults (16, 17). However, physical activity correlations with weather were not significantly explained by physical functioning status for these subjects (17). We did not encounter studies that report results of sleep pattern responses to weather variables and how the responses would be affected by the subject's physical functioning status.

The objective was to study if rest and activity patterns measured by an actigraph (wrist-worn) in daily living are associated with the self-reported functioning status of nursing home and assisted living facility residents without dementia, when actigraph data were collected in free living conditions. In addition, we study how the activity patterns' response to environmental stimuli (facility activity rhythm) is associated with the self-reported functioning status. We also present two cases where changes in the activity and sleep patterns can be associated with the changes in functioning over time.

Methods

Material and subjects

The study material was collected from two nursing homes and from two assisted living facilities in Finland. The facilities were selected because the actigraph system was already installed there, and the residents and the personnel were familiar with the system. The inclusion criteria were willingness to participate in the study. The exclusion criteria were chronic disease seriously affecting wrist movements, having an acute disease, or having a disturbing event such as surgery during the recording. All the subjects gave a written consent. The study was accepted by the Regional Ethics Committee of the Northern Ostrobothnia Hospital District. For the analysis, we excluded the data from persons with dementia, since the actigraphy data can differ between people with and without dementia (6), possibly due to the disrupted sleep-wake cycle related to dementia. The dementia criterion

was set at the Mini Mental State Examination (MMSE) score of below 21 and the Clinical Dementia Rating (CDR) score of above 0.5. Actigraph data and functioning measures from 36 subjects were included in the cross-sectional analysis (29 females, average age 80.4 years with standard deviation (SD) of 9.0 years, MMSE average score of 26.7 with SD of 3.0). Since the actigraph system stores the data on the facility's server by default, we were able to access very long recordings for seven subjects. From these, two representative recordings were selected for presentation.

Health and functioning measures

The health and functioning status was assessed with a questionnaire on activities of daily living. The questionnaire included 14 items on a four-point scale (18). The grades describe the difficulty in performing an activity (without difficulty=1 / with difficulty, but without help=2 / only with help=3 / not able to perform=4). Subjects were asked to evaluate whether they were able to move outdoors, walk between rooms, use stairs, walk at least 400 meters, carry a heavy object, use the toilet, wash themselves, dress and undress, get in and out of the bed, prepare food, feed themselves, cut their toenails, do light housework, and do heavy housework. We have used the sum of all the components' scores to describe the functioning status of a subject in the analysis. Similar questionnaires are reported to have 0.85-1.0 inter-rater reliability and 0.8-0.99 test-retest correlations (19). The ADL questionnaire has very similar content with the widely used Katz Index (ADL) and Brody scale (IADL). Experienced researchers collected the data using face-to-face interviews.

Equipment (actigraphy)

The actigraph device in the study is a wrist-worn online activity monitor (IST WristCare, Vivago, Helsinki, Finland; www.vivago.fi, telemetric actigraph), which can observe a person's minute-to-minute activity level and sleep/wake patterns continuously (20). The sensing modality in the device detects micro- and macro-movement of the wrist, which is transformed to an activity epoch value for each minute (in arbitrary units). In addition, the device monitors wearing adherence (detection of whether the device is on the wrist) based on skin conductivity measurement (20). This helped care personnel to remind the subjects to wear the device if they forgot to put it on after a removal (for example due to shower or sauna). The telemetric actigraph's primary purpose of use is as a social alarm device (panic button on a wrist-worn device). The system is reported to perform sleep/wake classification with a similar accuracy to a traditional actigraph when compared with polysomnography (the golden standard in sleep research) (21). In addition, it is found to be highly sensitive in detecting self-reported naps among older adults (21). During the study, the minute-to-minute activity data were stored automatically on an institute's central computer, from

which the data were extracted and anonymised before the analysis.

Actigraphy data analysis procedures

Most commonly, actigraphy is used to record a user's activity levels, circadian rhythm parameters, and sleep/wake patterns objectively (5). Since there is a vast number of processing methodologies targeted at actigraphy data, we intended to select the most typically reported parameters for quantifying sleep and activity rhythm patterns in studies with similar objectives to ours. A new analysis method for describing an activity behaviour response to an environmental stimulus (in this case, a facility's joint activities, such as meals and social events) was created. With the measure, we intend to study a stimuli-response relationship with the health status of older people (13). In addition, a manufacturer-specific parameter for describing diurnal activity rhythm strength was selected in the analysis. Since the reliability of the wrist-worn actigraphy data analysis procedures is reported to benefit even from two weeks' measurement (22), we targeted data samples of 14 days in length, but accepted recordings of at least 7 days in length.

The following procedures and parameters were included in the analysis:

An estimation of activity pattern's fit on 24-hour sinusoidal wave (the procedure fits a single 24-hour cosinor function with an actigraphy minute-to-minute data). The analysis results values for mesor (MESOR, mean of the activity data), amplitude (AMPL, difference between mesor and the peak of the fitted waveform), and acrophase (PHASE, timing of the activity rhythm for example peak at 15:48 that is 3:48 PM) (23). MESOR and AMPL are in the device specific activity units.

The 24-hour autocorrelation (AUTOCORR) describes the similarity of the activity rhythm (24) between days, and was selected because the physical activity is assumed to vary with a 24-hour rhythm. In practice, the analysis compares the actigraphy time series data to itself with a 24-hour delay (1440 minutes). The values vary between one for perfectly matching data, and minus one when the phase (that is the daily activity timing) is exactly the opposite, while a value close to zero indicates a large day-to-day variation in activity patterns.

The circadian rhythm parameters, inter-daily stability (IS), intra-daily variability (IV), and relative amplitude (RA) are frequently reported in the studies including a similar type of subject as in the current analysis. IS describes the stability between the days, implying a stable activity rhythm. IS values vary between one for a perfect match between the days and zero for very arrhythmic activity behaviours. IV quantifies the fragmentation of the rhythm and activity. IV gets small values for sine-wave-like data and values close to two for highly disrupted activity patterns. For example, it was reported that a high IV value (>1) was an indication of daytime naps and/or night-time awakenings (25). RA is the normalised ratio

between the most active 10 hours and the least active 5-hour periods (13, 14). The most significant difference for IV, IS and RA calculations compared to the other utilized procedures is that the minute-to-minute activity data is at first converted to present the active minutes count for each hour (14). For the telemetric actigraph, minute-epochs with a value of four or above were categorized as active. The threshold selection was based on a concurrent validation analysis between traditional (Actiwatch, Cambridge Neurotechnology in 2003) and telemetric actigraph (data not shown). The selected threshold yielded the strongest correlation and the smallest error between these two recording devices for the IV, IS and RA parameters. A more detailed description of the calculation of the IV, IS and RA parameters is described in related research (14).

Total sleep time (TST), daytime sleep/passivity amount (NAP), sleep efficiency (SE, percentage of sleep when in bed), and number of awakenings (AWAKN) and night-time activity deviation (NIGHT ACT) present sleep patterns indices in the analysis. TST and NAP are based on the minute-to-minute sleep/wake classifications provided by the telemetric actigraph (typical output of an actigraph device). The subjects or the nursing personnel wrote down the bed times (going to sleep and getting out of bed) during the study, which were used in the calculation of TST and SE. A single researcher visually observed the quality of sleep log markings and removed potential false values. NAP is a sum of sleep detections during the daytime between 9 am and 9 pm. The same daytime period was used in related research (6). Awakenings (AWAKN) were counted by detecting the transition from sleep to wake when in bed. NIGHT ACT is the standard deviation of the activity signal while in bed, and it is supposed to provide information about sleep quality/restlessness (26). A manufacturer-specific parameter describing circadian rhythm strength (CRS) was calculated by dividing night-time activity (11 pm to 5 am) with the activity of the previous day (8 am to 8 pm) (27).

A new indicator was created to describe how much a personal activity correlates with an institute's joint activity (named housing correlation (HOUSE)). The indicator is formed with a following procedure:

1) A period close to ADL inquiry which included 14 days of actigraph data for the subject of interest and which included actigraph data from other residents without a major interruption was identified. 2) The actigraph data from each subject were normalized and smoothened (scaled from zero to one and filtered with a 60-minute moving average). This helps to reduce differences between the subjects' mean activity levels and better synchronises the timing of the common activities between the individuals. 3) These normalized actigraph data are averaged for each minute over all the residents (excluding the person of interest). This combined 14-day long activity data is called a grand average. 4) From the grand average common, facility-specific active periods are identified by subtracting the mean of the daytime grand average activity for each day and preserving only positive values (the timestamps of the

daytime were identified from the grand average for each day individually using ad hoc threshold values). This residual data were considered to represent facility activities such as meals or social events (see Fig. 1). 5) The Pearson correlation was calculated for each subject, between the individual's actigraph data and the grand average-based facility activities data.

This procedure forms the HOUSE indicator that is close to 1 for perfect synchrony between the facility activities and the individual's activity, and close to zero for poor synchrony.

Figure 1

Example of three days of grand average data after daily mean level removal which intends to represent common activities of the facility. Units are normalized and averaged values of the activity epochs and do not associate with the original actigraph data well. Time is given in x-axis
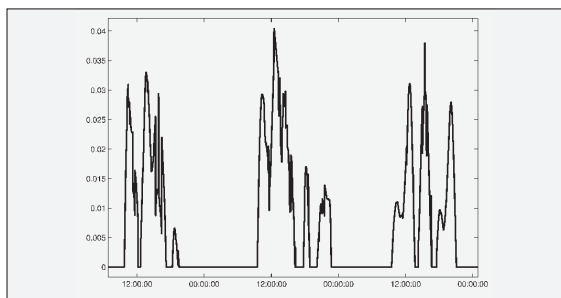
Statistical analysis

To discover associations between functioning and activity behaviours, the Spearman correlation coefficients were calculated between the actigraphy parameters and the ADL score. Spearman correlation analysis was selected because the ADL score is on an ordinal scale. To discover possible u-shape correlations, a regression analysis, including a quadratic term, was performed. We manually selected actigraph data close to the ADL inquiry for the actigraphy parameter extraction.

To study how the functioning level affected the activity behaviours' indicators (especially the absolute values), we divided the subjects into two groups: whether or not they reported difficulties in performing an activity at most in three daily activities (independent N=22, dependent N=14). The difference in the actigraphy parameters between these two subgroups was studied using the t-test (the Kolmogorov-Smirnov test supported the parameters' normal distribution).

To study how the parameters behaved on an individual level, we visually observed long-term actigraph recordings and present two cases that we consider to represent well the topic and the monitoring challenge. The analyses were done only qualitatively. We analysed the correlation between weather variables and sleep and activity behaviour in these case recordings. We obtained the daily weather data of the subjects' residential location during the time periods of the

actigraph recordings from the Finnish Metrological Institute (http://en.ilmatieteenlaitos.fi/). The received data contained the daily temperature, atmospheric pressure, wind speed, and sunlight amount (minutes when direct irradiance from the sun was above 120 W/m2). The weather variable data were used as received in the analysis. The analyses were performed in Matlab (Matworks Ltd., www.matworks.com, Natick, Massachusetts, U.S.A.) and in IBM SPSS Statistics (IBM, www.ibm.com, Armonk, U.S.A.).

Results

The Spearman rank correlations between ADL and the actigraphy parameters are presented in Table 1. The ADL questionnaire average score was 27.8 (SD 10.0) for all users, 33.0 (SD 9.2, N=21) for nursing home residents, and 22.2 (SD 8.2, N=15) for assisted living facility residents. The significance levels are adjusted using the Bonferroni method to control for multiple comparisons. The average actigraph data length was 13.7 days and the average missing data was 4.7 percent. Five cases did not have a sleep diary, and the sleep parameters are analysed for 31 cases (SE, TST, AWAKN, and NIGHT ACT). TST (P=0.013 after Bonferroni correction) had a u-shape connection with ADL. The correlations between the activity rhythm parameters and ADL did not change significantly when controlled for activity level (cosinor mesor) and age in a partial Spearman correlation analysis.

Table 1

Spearman rank correlation coefficient and p-value of the test between Activities of Daily Living questionnaire (ADL) and actigraphy parameters. Significance levels are corrected and p-values values are not corrected using the Bonferroni method

Parameter	ADL	p-value
Activity levels		
Cosinor mesor (MESOR)	-0.49*	0.003
Cosinor amplitude (AMPL)	-0.42	0.011
Activity rhythm		
Circadian rhythm strength (CRS)	0.10	0.582
Interdaily stability (IS)	0.25	0.136
Intradaily variability (IV)	0.35	0.038
Relative amplitude (RA)	0.27	0.106
Cosinor acrophase (PHASE)	0.09	0.624
24-hour autocorrelation (AUTOCORR)	0.32	0.054
Housing rhythm correlation (HOUSE)	-0.44†	0.007
Sleep parameters		
Night-time standard deviation (NIGHT ACT)	-0.69‡	<0.001
Daytime sleep/passive amount (NAP [minutes])	0.14	0.424
Total sleep time (TST [minutes])	0.04	0.826
Number of awakenings (AWAKN)	0.21	0.257
Sleep efficiency (SE [percentage])	-0.14	0.456

The significance levels are flagged with *P < 0.05, ‡P < 0.01, †P<0.1

Table 2
Actigraphy parameter values (mean and standard deviation, SD) for two independence groups (the division is based on the number of self-reported disabilities: independent = three or less disabilities). The p-values of the t-test are not Bonferroni corrected

Parameter	Independent mean (SD), N=22	Dependent mean (SD), N=14	p-value
Activity levels			
Cosinor mesor (MESOR)	12.8 (7.6)	8.2 (6.3)	0.069
Cosinor amplitude (AMPL)	8.0 (5.4)	4.3 (3.7)	0.027
Activity rhythm patterns			
Circadian rhythm strength (CRS)	0.28 (0.18)	0.37 (0.23)	0.319
Interdaily stability (IS)	0.46 (0.22)	0.54 (0.19)	0.205
Intradaily variability (IV)	0.55 (0.15)	0.71 (0.21)	0.100
Relative amplitude (RA)	0.58 (0.24)	0.60 (0.25)	0.756
Cosinor acrophase (PHASE)	13:56 (1:57)	14:10 (1:53)	0.816
24-hour autocorrelation (AUTOCORR)	0.42 (0.15)*	0.53 (0.15)	0.002
Housing rhythm correlation (HOUSE)	0.32 (0.09)	0.25 (0.11)	0.026
Sleep parameters			
Night-time standard deviation (NIGHT ACT)	8.7 (4.3)*	4.2(2.7)	0.003
Daytime sleep/passive amount (NAP [minutes])	97(92)	133(67)	0.192
Total sleep time (TST [minutes])	365 (70)	341 (153)	0.622
Number of awakenings (AWEKN)	3.1 (1.2)	3.8(1.3)	0.150
Sleep efficiency (SE [percentage])	75 (13)	60 (28)	0.095

* $P<0.05$ after Bonferroni correction.

Table 2 presents the t-test analysis results between the two groups of subjects, divided according to the number of the self-reported disabilities.

When observing individual cases the associations between actigraph data changes and estimated functioning state varied between individuals. The indicators and the actigraph data were visually studied via two types of figures (see examples from Fig. 2 and Fig. 3). Sub-figure A shows actigraph data (activity level value for each minute) for each 48 hours in the y-axis starting at midnight. The darker the point is in the Sub-figure A, the higher the activity level for that particular minute is. The actigraph data is smoothened by averaging the values over seven days to highlight the behavioural patterns. The graph type in the Sub-figure A is called double plotted actogram and it is utilized widely in the actigraphy research. The Sub-figure B is a collection of bar diagrams for selected actigraphy parameters for the same time frame as the actogram in the Sub-figure A.

Figure 2 is a case example of actigraph data from a 78-year-old male with an ADL total score of forty at the end of the recording (a score of 14 represents the best and 56 the worst). It may be observed from Sub-figure B that timing of the activity becomes earlier (decreasing trend of PHASE) that is visually observable in Sub-figure A as well. The decreasing activity level (AMPL) is well presented in Sub-figures A and B. In addition NIGHT ACT, IS, and AUTOCORR decreased along the suspected declining condition. However, especially NIGHT ACT increased after the last missing data period (beginning of the period of interest marked with a star in Figure 2 A) and AUTOCORR decreased, which are slightly opposite to the group findings when assuming that the subject's condition is worsening. CRS and IV both react strongly after the last missing data section, around May 2008 (marked with a star). TST does not have strong, systematic changes during the measurement.

Figure 3 presents the second case example (83-year-old female with an ADL score of 15). There were only minor changes in her activity behaviour in the 1069-day-long actigraph recording. According to Sub-figure A (Fig. 3), evening activity decreases, which is visible in advance of PHASE and the lowering of AMPL. IV mildly increases (more fragmented activity behaviour), indicating slightly deteriorating functioning, in accordance with the related research (14, 15).
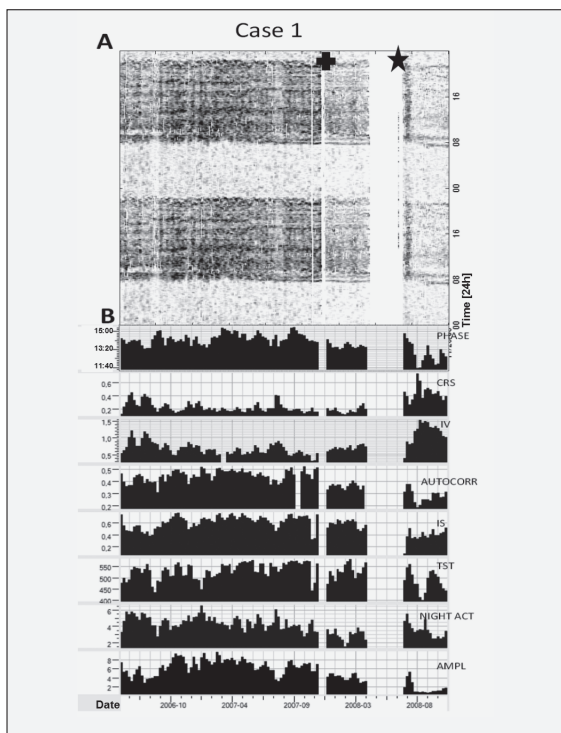
External influences may also be sporadically observed in the activity patterns of the case examples. For example, we noticed that in the data of Case 2, PHASE tends to follow a six-month rhythm (according to numerical analysis; autocorrelation and Fourier analysis, data not shown) with the zenith in late June

and at the turn of the year. In addition, in the data of Case 2, night-time actigraphy deviation (NIGHT ACT) correlated with daily sunlight duration (Spearman rho= 0.21, P < 0.05); the shorter dark time at night during the summer possibly making sleep more restless. A similar trend was not present in the data of Case 1. However, in Case 1 data the outside temperature and daytime activity level (average of activity values between 8 am and 8 pm) had a negative correlation (rho= -0.25, P< 0.05) between the beginning of the monitoring and the first missing data section (marked with a plus sign in Figure 2), suggesting that during the warmer days, the subject was more passive.

Figure 2

907-day actigraph recording of Case 1. Sub-figure A is a double plotted actogram for minute-to-minute activity data. Each column presents 48 hours of activity data epochs. The samples are darker if the activity is higher. Pure white coloured sections are missing data. The minute-to-minute activity data are averaged over 7 consecutive days to highlight long-term activity behaviour patterns. Sub-figure B presents selected actigraphy parameters: Cosinor acrophase (PHASE [time]), Circadian rhythm strength (CRS), Intradaily variability (IV), Autocorrelation function of 24-hour lag (AUTOCORR), Interdaily stability (IS), Total sleep time (TST [minutes]), Night-time standard deviation of the actigraphy (NIGHT ACT), and Cosinor amplitude (AMPL [activity level])

Figure 3

A 1069-day actigraph recording named Case 2. Sub-figure A is a double plotted actogram for minute-to-minute activity data. Each column presents 48 hours of activity data epochs. The samples are darker if the activity is higher. Pure white coloured sections are missing data. The minute-to-minute activity data are averaged over 7 consecutive days to highlight long-term activity behaviour patterns. Sub-figure B presents selected actigraphy parameters: Cosinor acrophase (PHASE [time]), Circadian rhythm strength (CRS), Intradaily variability (IV), Autocorrelation function of 24-hour lag (AUTOCORR), Interdaily stability (IS), Total sleep time (TST [minutes]), Night-time standard deviation of the actigraphy (NIGHT ACT), and Cosinor amplitude (AMPL [activity level])

Discussion

We studied whether the function status of older adults (the ability to perform daily activities) is associated with activity and sleep behaviours quantified using an actigraph device in free-living, assisted living facilities and nursing home settings. In addition to traditional actigraphy indices, we included methods that intend to quantify subjects' sleep and activity behaviour responses to external stimuli, such as institute's daily activities and local weather patterns.

The results indicate an association between the activity level

and the ADL score, which is in line with the related literature (25, 28, 29). The finding did not change when controlled for age. However, the activity level did not differ statistically between subjects when divided into two groups, according to the ADL assessment, possibly due to the large variation in the activity levels between the subjects and the moderate number of subjects. The fact that the utilised actigraph was not able to record activity when a subject was out of range of the facility (connection between a receiver unit and a telemetric actigraph unit was lost) might have disturbed the result slightly. In the cosinor analysis the out of range periods were coded as missing data. A more preferred solution in general would be to log the activity data when the sensor is outside the base station range and send the data for the receiver unit afterwards.

Most of the sleep parameters (total sleep time, efficiency, and awakenings) did not show significant correlation with ADL in this dataset. However, according to the polynomial regression (added quadratic term), there tends to be a U-shaped connection between functioning and total sleep time. Similar types of findings with sleep time have been reported in other studies, as well (7, 10). However, there is still little data showing that improving sleep habits would reduce different health risks for older people (30). In addition, it should be considered that the reliability of actigraphy decreases as the fragmentation of sleep increases (5). Night-time activity variability (night-time standard deviation) of the actigraph data had negative correlation with functioning, suggesting that more varying activity during the night could imply better functioning.

Some of the parameters describing diurnal activity patterns indicated association with functioning. The more dependent subjects tend to have a more stable activity rhythm (according to autocorrelation). The similarity of activity rhythm (IS) and the higher activity rhythm association with the facility's common activities (HOUSE) had a trend with a functioning status (with a significance level of P<0.1). Some of the results actually suggest that, in the institutional settings, varying activity behaviour (according to interdaily stability and night-time variance) might imply better health for people without dementia. This is somewhat opposite than encountered in the related literature for people with dementia (9, 15).

Our indicative results suggest that external stimuli such as facility activities and local weather patterns affect the behaviour of older individuals, and that these influences might differ according to subjects' levels of functioning. This observation is supported both by quantitative group analysis (housing rhythm correlation with ADL) and qualitative case analysis. In latitudes similar to Finland, the amount of sunlight and the length of the day vary significantly during the year. In addition, the nursing home environment can disrupt stable activity rhythms and sleep/wake patterns through limited exposure to sunlight, long periods spent in bed, physical inactivity, and a disruptive night-time environment (11). These set challenges for people in maintaining their circadian rhythm, and individuals with poor functioning may be more vulnerable to these factors. However, due to the small amount of data, these indications are at the level of a hypothesis and need further study. In addition to more thorough hypothesis testing with a larger sample size, multilevel data analysis would be needed to study how much the different parameters overlap, and how much independent information they actually provide.

The limitation of the study was the small sample size and the heterogeneous subject group, due to which some of the results are indicative rather than conclusive. The telemetric actigraph's minute-to-minute activity value is also somewhat device specific, and generalising the results to other similar devices should be done with caution. However, the outputs of traditional actigraphs are also different between brands, and it is unlikely that the results would change significantly if a traditional actigraph would be used.

Conclusions

The results suggest that more activity during daytime and more variance in activity patterns are associated with a better functioning status in this study population.

Since the environmental stimuli tend to affect the subject's activity and rest behaviour, this should be considered in related research. In addition, studying how the subjects react to these environmental stimuli, such as weather patterns or assisted living facility activities, may provide new information on a subject's functioning state, especially in the preclinical phase. However, more research, especially longitudinal, is needed on the topic. The actigraphy measures describing activity rhythm patterns can potentially be a new insight for monitoring health status, and health changes among older people in the nursing homes and assisted living facilities.

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Title	**Actigraphy in evaluation and follow up of physical functioning of older adults**
Author(s)	Juho Merilahti
Abstract	For older adults, physical functioning status describes how well a person is able to manage necessary daily activities independently. Different tools exist for testing and follow-up of physical functioning state at different levels of health and age. However, technologies have not been widely adapted for monitoring the physical functioning status during daily life in a longitudinal setup. In this thesis, the actigraph's characteristics for evaluating the physical functioning of older adults at various levels of health and functioning are studied. An actigraph measures activity level estimates continuously and is typically worn on the wrist for extended periods. The actigraph is a mature technology that has been used in the sleep research since 1970s. In addition to sleep patterns, the actigraph can assess a subject's physical activity levels, and sleep-wake rhythms. Furthermore, a novel processing concept for evaluating long-term activity pattern responses to external stimuli, such as facility's common activities or weather has been developed in this thesis. This thesis utilizes three different datasets in which actigraph data have been collected online, parallel with physical functioning estimates. The first dataset includes subjects from a nursing home with intermediate to demanding care need, the second dataset subjects are assisted living residents who are mostly independent but might receive some support services, and the third dataset subjects are from a demanding nursing home unit. The third dataset includes longitudinal data (over three years at longest). In addition, a fourth dataset was used to compare the actigraph processing methods between a traditional actigraph and the online actigraph to understand how well the encountered results with datasets 1–3 could be generalized. In the thesis, the actigraph estimates for sleep, activity level and diurnal rhythms are compared with physical functioning results by utilizing datasets 1–3. In combined data from datasets 1 and 2 (demented subjects were excluded from the analysis) higher physical functioning estimate (activities of daily living assessment) was associated with higher physical activity level and with more night-time activity variance. In addition, subjects with better functioning tend to have more similar activity rhythms with the facility activities (novel concept) and less-stable day-to-day activity patterns. In Dataset 3 (now including subjects with and without dementia) better physical functioning was associated with more stable and stronger diurnal activity rhythm. However, the correlation between the diurnal rhythm stability and physical functioning might be explained by the severity of dementia according to the results. In the longitudinal case analysis, most of the activity rhythm patterns were associated with physical functioning changes as expected according to cross sectional analysis. In Dataset 2, the amount of time the subjects spent outside the facility correlated positively with better physical functioning. This suggests that different context information can provide meaningful information on the older adults' health in addition to traditional actigraph estimates. Since the correlations slightly differed depending on the study population we suggest that monitoring activity level, activity rhythm strength, similarity and variability simultaneously is recommended. Sleep patterns were not connected with physical functioning in the utilized datasets. The thesis results suggest that the actigraph is a feasible health monitoring concept to be utilized in assisted living and nursing home settings and is suitable for follow up of changes in activity patterns associated with changes in physical functioning.
ISBN, ISSN, URN	
Date	December 2017
Language	English, Finnish abstract
Pages	88 p. + app. 62 p.
Name of the project	
Commissioned by	
Keywords	Activities of daily living, sleep, circadian rhythm, actigraphy, nursing home, assisted living. physical activity
Publisher	

Nimeke	**Aktigrafia ikääntyneiden toimintakyvyn arvioinnissa ja seurannassa**
Tekijä(t)	Juho Merilahti
Tiivistelmä	Ikääntyneiden toimintakyky kuvaa heidän mahdollisuuksiaan itsenäiseen suoriutumiseen ja kapasiteettia osallistua erilaisiin aktiviteetteihin yhteiskunnassa. Toimintakyvyn testaamista varten on olemassa lukuisia menetelmiä eri elämänvaiheisiin. Vielä ei kuitenkaan ole hyviä työkaluja jatkuvaan toimintakyvyn mittaamiseen ja arviointiin arjen lomassa. Tässä väitöskirjassa tutkitaan aktigrafian mahdollisuuksia arvioida ikääntyneen henkilön toimintakykyä. Aktigrafi on kellomainen laite, joka mittaa käyttäjänsä fyysistä aktiivisuutta pitkäkestoisesti. Aktigrafiaa on käytetty erityisesti unitutkimuksessa jo 1970-luvulta asti. Unen keston ja laadun arvioinnin lisäksi sillä voidaan seurata käyttäjänsä aktiivisuuden määrää ja aktiivisuuden vuorokautista rytmisyyttä. Väitöskirjassa on lisäksi selvitetty aktigrafian mahdollisuutta arvioida henkilön käyttäytymismuutosta johonkin ulkoiseen ärsykkeeseen, kuten laitoshoidon palvelurytmiin tai sään vaihteluihin. Väitöskirjan analyysit perustuvat kolmeen tutkimusaineistoon. Kaksi aineistoa koostuu laitoshoidon asukkaiden ja yksi palveluasumisen asiakkaiden rekisteröinneistä. Toinen laitoshoidon aineistoista sisälsi pitkittäisrekisteröintejä useamman vuoden ajalta. Väitöskirjassa hyödynnettiin lisäksi neljättä aineistoa tutkimuksissa käytetyn aktigrafin (Vivago) tulosten yleistettävyyden arvioimiseksi. Tulosten mukaan aktigrafimittausten tulisi olla lyhyimmillään viikon mittaisia luotettavien mittaustulosten (esimerkiksi uni ja aktiivisuus) saavuttamiseksi. Tutkimuksissa käytetyn aktigrafin havaittiin vastaavan perinteistä aktigrafia erityisesti arvioitaessa käyttäjän aktiivisuus- ja unirytmejä. Väitöskirjassa havaittiin useamman aktigrafian tunnusluvun olevan yhteydessä muilla menetelmillä (kyselyt ja toiminnalliset testit) arvioituun toimintakykyyn. Heterogeenisessa vanhusväestössä korkeampi toimintakyky assosioitui korkeampaan aktiivisuustasoon sekä päivä- että yöaikana. Lisäksi paremman toimintakyvyn omaavat henkilöt toteuttivat asumiskohteen keskimääräisiä aktiviteetteja paremmin kuin heikommassa kunnossa olevat. Homogeenisemman laitoshoidon ryhmän aineiston mukaan toimintakyvyn matalampi taso assosioitui heikompaan ja rikkonaisempaan vuorokautiseen aktiivisuusrytmiin. Myös erilaisiin konteksteihin liittyvät havainnot aktigrafiassa, kuten ulkoilut, voivat kertoa tulosten mukaan henkilön toimintakyvyn tasosta objektiivisesti. Koska aktigrafista laskettavien tunnuslukujen ja toimintakyvyn yhteys on joiltain osin riippuvainen kohderyhmän terveydentilasta, on suositeltavaa seurata rinnakkain henkilön aktiivisuustasoa, aktiivisuusrytmin samankaltaisuutta, voimakkuutta ja yhtenäisyyttä, jotta mahdolliset terveydelliset muutokset voidaan havainnoida ennakolta. Unikäyttäytymisen ja toimintakyvyn välillä ei havaittu systemaattista yhteyttä. Tulosten mukaan aktigrafian avulla seurattavat käyttäytymissuureet voivat luotettavasti indikoida terveydentilaa ja siinä tapahtuvia muutoksia.
ISBN, ISSN, URN	
Julkaisuaika	Joulukuu 2017
Kieli	Englanti, suomenkielinen tiivistelmä
Sivumäärä	88 s. + liitt. 62 s.
Projektin nimi	
Rahoittajat	
Avainsanat	Päivittäiset toiminnot, uni, vuorokausirytmi, aktigrafia, hoitokoti, palveluasuminen, fyysinen aktiivisuus
Julkaisija	

Actigraphy in evaluation and follow up of physical functioning of older adults

For older adults, physical functioning status describes how well a person is able to manage necessary daily activities independently. Different tools exist for testing and follow-up of physical functioning state at different levels of health and age. However, technologies have not been widely adapted for monitoring the physical functioning status during daily life in a longitudinal setup. In this thesis, the actigraph's characteristics for evaluating the physical functioning of older adults at various levels of health and functioning are studied. An actigraph measures activity level estimates continuously and is typically worn on the wrist for extended periods. The actigraph is a mature technology that has been used in the sleep research since 1970s. In addition to sleep patterns, the actigraph can assess a subject's physical activity levels, and sleep-wake rhythms. In the thesis, a novel processing concept for evaluating long-term activity pattern responses to external stimuli, such as facility's common activities or weather has been developed.

This thesis utilizes three different datasets in which actigraph data have been collected online, parallel with physical functioning estimates.The results suggest that the actigraph is a feasible health monitoring concept to be utilized in assisted living and nursing home settings and is suitable for follow up of changes in activity patterns associated with changes in physical functioning. However, sleep patterns were not connected with physical functioning in the utilized datasets.