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Motion Sensor-Based Monitoring of Physical Activity in Older Adults

Current Approaches and Clinical Applicability

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Hereby I declare:

The work presented in this thesis is the original work of the author except where acknowledged in the text. This material has not been submitted either in whole or in part for a degree at this or any other institution. Those parts or single sentences, which have been taken verbatim from other sources, are identified as citations. I further declare that I complied with the actual "guidelines of qualified scientific work" of the German Sport University Cologne.

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29. Mai 2024

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Summary

This thesis addresses the use of motion sensor-based approaches to assess and monitor physical activity as input into interventions for older adults, specifically in geriatric health care settings. The work, as part of this thesis, pursues the following aims: (1) to compare the outcomes from different physical activity assessment approaches and the implications for their clinical applicability; (2) to investigate the associations of self-reported chronotypes with the circadian aspects of mobility; (3) to explore how circadian aspects of mobility-related behavior and clinical characteristics in dementia relate; and (4) to give an overview how on motion-sensor based monitoring of physical activity is currently used to guide and personalize physical activity interventions in geriatric health care.

A key finding is, that usually applied, intensity-based assessment approaches (e.g., actigraphy) are not recommendable in older adults, as they do not address the core aspects of physical activity in old age (i.e., performance functional activities such as standing and walking as well as engagement in sedentary behavior). The comparison of different physical activity assessment approaches within this thesis revealed that a mobility-related assessment of physical activity, however, can provide clinically applicable outcomes of overall physical activity and sedentary behavior in older adults. In a proof-of-concept study, this thesis presented a novel approach using mobility-related physical activity outcomes to analyze circadian aspects of physical activity and compared it to the self-reported individual diurnal preference (known as chronotype). A temporal correspondence between the daytime of peak gait activity and the individual chronotype in relatively healthy older adults were found. The timing of peak mobility-related behavior may constitute an innovative approach to monitor changes in physical activity behavior and personalize physical activity interventions. Building on this, this thesis explored how the diurnal timing of peak gait activity as well as nocturnal gait activity relate to clinical characteristics of patients in acute dementia care. The analyses revealed a large variability and differences in the timing of peak gait activity between patients and a high incidence of gait activity in acute dementia care. Nocturnal gait activity was associated to higher caregiver burden and more pronounced neuropsychiatric symptoms (i.e., symptoms of sleep and nighttime behaviors disorders). Analyzing the nocturnal gait activity as well as the diurnal timing of peak gait activity seem to provide clinical applicable information on the circadian aspects of mobility-related and may be used to personalize (non)-pharmacological treatment in acute dementia care. Subsequently, a scoping review was conducted to investigate how motion sensor-based monitoring is currently applied to guide and personalize physical activity interventions in geriatric health care. The results show a large heterogeneity in existing motion-sensor monitoring-based physical activity interventions. Furthermore, it seems that the potential of monitors with regard to the use of physical activity data to personalize interventions goals and feedback has not been exploited to the fullest yet. Future studies should focus on determining which intervention components are most effective in improving physical activity and especially sedentary behavior, investigate the effects of personalized physical activity goals and how physical activity monitor based interventions can be applied over the continuum of geriatric health care. Furthermore, the clinical validity of the proposed approach to analyze circadian aspects of physical activity based on mobility-related physical activity outcomes need to be tested. The findings of this thesis reveal important information on clinical applicable approaches using motion sensor-based monitoring to assess and intervene on physical activity in older adults and specifically in geriatric health care settings.

Zusammenfassung

Die vorliegende Dissertation befasst sich mit bewegungssensorbasierten Ansätzen zur Erfassung der körperlichen Aktivität älterer Erwachsener, insbesondere in geriatrischen Gesundheitseinrichtungen, und zur Gestaltung von Bewegungsinterventionen. Die Arbeit im Rahmen dieser Dissertation verfolgt vier Ziele: (1) Vergleich der Ergebnisse verschiedener Ansätze zur Erfassung der körperlichen Aktivität und Bewertung der Implikationen der verschiedenen Ansätze für die Beurteilung der körperlichen Aktivität in der klinischen Anwendung; 2) Vergleich der zirkadianen Aspekte der mobilitätsbezogenen Aktivität zwischen den unterschiedlichen Chronotypen (3) Untersuchung des Zusammenhangs von zirkadianen Aspekten der mobilitätsbezogenen Aktivität und klinischen Merkmalen bei Demenz; und (4) Bereitstellung eines Überblicks darüber, wie die Bewegungssensorbasierte Erfassung der körperlichen Aktivität derzeit genutzt wird, um Interventionen zur Förderung der körperlichen Aktivität in der geriatrischen Gesundheitsversorgung zu gestalten und zu personalisieren.

Ein Hauptergebnis ist, dass die üblicherweise verwendeten intensitätsbasierten Ansätze (z.B. Aktigraphie) für ältere Erwachsene nicht empfehlenswert sind, da sie die Kernaspekte der körperlichen Aktivität im Alter nicht berücksichtigen (d.h. die Durchführung funktioneller Aktivitäten wie Stehen und Gehen sowie das Ausüben sitzender Verhaltensweisen). Der Vergleich verschiedener Ansätze zur Erfassung der körperlichen Aktivität im Rahmen dieser Arbeit hat gezeigt, dass eine mobilitätsbezogene Erfassung der körperlichen Aktivität klinisch anwendbare Ergebnisse zur allgemeinen körperlichen Aktivität und zum Bewegungsverhalten älterer Menschen liefern kann. In einer Proof-of-Concept-Studie wurde ein neuartiger Ansatz vorgestellt, der mobilitätsbezogene Parameter zur Analyse zirkadianer Aspekte der körperlichen Aktivität verwendet und mit der selbstberichteten individuellen Tagespräferenz (bekannt als Chronotyp) vergleicht. Es zeigte sich eine zeitliche Übereinstimmung zwischen der Tageszeit der höchsten Gehaktivität und dem individuellen Chronotyp bei relativ gesunden älteren Erwachsenen. Die Analyse zirkadianer Aspekte der körperlichen Aktivität könnte ein innovativer Ansatz für die Früherkennung und individuelle Anpassung der Behandlung von Störungen des zirkadianen Rhythmus im Alter und in der geriatrischen Versorgung sein. Darauf aufbauend wurde in dieser Arbeit untersucht, wie die Tageszeit der maximalen Gangaktivität sowie die nächtliche Gangaktivität mit klinischen Merkmalen von Patient*innen mit Demenzerkrankungen in der Akutversorgung zusammenhängen. In der Analyse zeigte sich eine große Variabilität hinsichtlich des Zeitpunkts der maximalen Gangaktivität zwischen den Patient*innen und eine gesteigerte Häufigkeit der nächtlichen Gangaktivität in der Akutversorgung von Demenzerkrankungen. Nächtliche Gangaktivität wurde mit einer höheren Belastung der Pflegekräfte und ausgeprägteren neuropsychiatrischen Symptomen (d. h. Symptome von Schlaf- und nächtlichen Verhaltensstörungen) assoziiert. Die Analyse der nächtlichen Gangaktivität sowie des Zeitpunkts der maximalen Gangaktivität am Tag scheint klinisch anwendbare Informationen über die zirkadianen Aspekte der Mobilität zu liefern und kann zur Personalisierung der (nicht-)pharmakologischen Behandlung in der akuten Demenz-versorgung genutzt werden. Im letzten Teil dieser Dissertation wurde in einem Literaturreview untersucht, wie die bewegungssensor-basierte Erfassung derzeit in der geriatrischen Gesundheitsversorgung zur Gestaltung und Personalisierung von Bewegungsinterventionen genutzt wird. Die Ergebnisse zeigen eine große Heterogenität bei den bestehenden bewegungssensorbasierten Interventionen. Das Potenzial von Bewegungssensoren im Hinblick auf die Nutzung der Bewegungsdaten zur Personalisierung von Interventionszielen und Feedback scheint noch nicht voll ausgeschöpft zu sein.

Künftige Studien sollten ermitteln, welche Interventionskomponenten zur Steigerung der körperlichen Aktivität und insbesondere zur Reduktion sedentärer Verhaltensweisen am wirksamsten sind. Des Weiteren sollten die Effekte personalisierter Interventionsziele analysiert werden und untersucht werden, wie bewegungssensorbasierte Interventionen über das gesamte Kontinuum der geriatrischen Gesundheitsversorgung hinweg angewendet werden können. Darüber hinaus muss die klinische Validität des vorgeschlagenen Ansatzes zur Analyse zirkadianer Aspekte der körperlichen Aktivität auf der Grundlage mobilitätsbezogener Parameter geprüft werden.

Die Ergebnisse dieser Arbeit liefern relevante Informationen zu klinisch anwendbaren Ansätzen, basierend auf Daten von Bewegungssensoren, um die körperliche Aktivität älterer Erwachsener, speziell in der geriatrischen Gesundheitsversorgung zu bewerten und zu verbessern.

Chapter 1

Introduction and Objectives

The proportion of older people in the global population is steadily increasing (World Health Organization (WHO), 2015). In Germany, the population of adults aged 65 years and older is estimated to increase from its current rate of 22% to 30% in 2050, with a particularly pronounced increase in the number of adults aged 80 years and older (Statistisches Bundesamt, 2019). An older population, with its associated increased incidence of chronic diseases, multimorbidity, and age-related diseases (Barnett et al., 2012), will challenge health care systems, which will be required to manage heightened utilization of their services (Robert-Koch-Institut, 2015) by a population that is immensely diverse in fitness level, health status, and cognitive capabilities. The result is intensifying pressure on health care systems worldwide (Kuzuya, 2019), highlighting the need for effective and efficient approaches to enable and maintain patients' access to care.

A physically active lifestyle is one key aspect of healthy aging (Bundesministerium für Gesundheit, 2012; WHO, 2015, 2017). However, the prevalence of physical inactivity increases with age. According to the Global Status Report on Physical Activity 2022, 40% of males and 45% of females aged 70 years or older in Europe do not meet the World Health Organization (WHO) minimum recommendations for physical activity (WHO, 2022). In Germany, one in two people above the age of 65 years is physically inactive (Lange & Finger, 2017). Physical activity levels are highly associated with all-cause mortality (Physical Activity Guidelines Advisory Committee, 2018; WHO, 2022). Recent evidence has shown that the relationship between physical activity and health is nonlinear, as even small positive changes in activity levels can benefit the least active older adults, who stand to profit most from increasing their activity engagement (Ekelund et al., 2019; Hansen et al., 2020). Existing physical activity programs, however, commonly employ a one-size-fits-all approach and do not address the heterogeneity among the older population in underlying health conditions (Brach et al., 2023). Furthermore, there is a bias in the current evidence towards short-term interventions in controlled-trial settings, causing long-term program implementation to be overlooked (Taylor et al., 2021). There is thus an urgent need for innovative and individualized approaches designed for long-term implementation over the continuum of care. The development of such interventions as a first step and their implementation and evaluation as a second step rely on the availability of clinically applicable methods of assessing physical activity in older adults in real-life conditions. To achieve this, assessment approaches must meet certain requirements in terms of their clinical relevance (e.g., facilitation of evidence-based decision-making, targeting of parameters relevant to the population of interest) and practical feasibility (e.g., usability, intelligibility of outcomes).

Recent technological advancements have caused a paradigm shift away from self-report assessments to device-based assessments of physical activity. The use of body-worn motion sensor devices enables the continuous monitoring of physical activity in real life, providing objective and rich information on whole-day physical activity accumulation over multiple days. The data collected by these devices have the potential to enhance the understanding of the profound influence of physical activity on health in old age and facilitate opportunities for clinicians to provide tailored physical activity advice. However, consistently applied strategies for assessing physical activity and monitoring interventions using motion sensors in older adults and geriatric health care settings are lacking.

This thesis addresses the use of motion sensor-based approaches to assess and monitor physical activity as input into interventions for older adults, specifically in geriatric health care settings. The remainder of this introductory chapter will highlight the importance of physical activity in older adults, address physical activity as a complex and multidimensional behavior, discuss current physical activity assessment tools, and review the existing evidence on physical activity interventions that employ physical activity monitoring. The thesis' research objectives and questions are derived at the end of this chapter.

Recommendations for physical activity in older adults

There is a generally accepted body of evidence supporting the positive effects of regular physical activity on physical and mental health. Both the initiation and maintenance of regular physical activity during aging reduce the risk of mortality (Stessman et al., 2009), and sufficient physical activity levels are associated with improved quality of life, mobility, and independent living, the latter constituting one of the primary health concerns of both older adults (Guthold et al., 2018) and health care systems.

Physical activity is defined as "*any bodily movement by skeletal muscles that results in energy expenditure*" (Caspersen et al., 1985). This formal definition specifically focuses on the physiological effects (i.e., energy consumption) of physical activity, and a large portion of the physical activity literature has consequently centered on the effects of physical exercise on energy consumption, mostly from the perspective of health outcomes. Based on estimations of energy expenditure expressed in metabolic equivalents of task (METs), physical activity is typically distinguished as vigorous (≥ 6 METs), moderate (≥ 3 METs), and light intensity (> 1.5 METs). Physical activity at a moderate-to-vigorous intensity for at least 150–300 minutes throughout the week is associated with substantial health benefits and is generally recommended by health organizations (WHO, 2020).

Not meeting physical activity recommendations (usually referred to as physical inactivity) is one of the leading contributors to global mortality (WHO, 2020), causing a substantial economic burden (Ding et al., 2016). The majority of older adults worldwide do not meet the evidence-based recommended minimum level of physical activity (Keadle et al., 2016). The

European Health Interview Survey in 2014/15 revealed that 62.2% of older women and 51.1% of older men (aged 65+ years) in Germany did not reach the recommendation of at least 2.5 hours per week of moderate-intensity physical activity (Lange & Finger, 2017). Furthermore, survey-based results indicated that, on average, older adults spent nine hours per day performing sedentary activities (Physical Activity Guidelines Advisory Committee, 2018; Walker et al., 2021). Emerging evidence has identified sedentary behavior as an independent risk factor for all-cause mortality (Physical Activity Guidelines Advisory Committee, 2018) and diminished physical functioning in older adults (Mañas et al., 2017; Wilson et al., 2021). The latest version of the WHO guidelines on physical activity from 2020 for the first time included recommendations for sedentary behavior; older adults are advised to limit their sedentary time by replacing sedentary behavior with physical activity of any intensity (Bull et al., 2020).

Knowledge of target group-specific determinants of physical activity is required when designing therapeutic interventions to increase physical activity (Brug et al., 2017). As part of an extensive international study, a panel of experts developed a theoretical framework that examined determinants of physical activity across the lifespan (Condello et al., 2016). The authors identified 106 determinants of physical activity behavior, of which health status was presented as an important factor whose influence on physical activity increases over the lifespan (Condello et al., 2016). Indeed, poor health status has been linked to higher amounts of sedentary behavior in older adults (Chastin et al., 2015). However, poor health does not constitute a contraindication to physical activity. Rather, considering the overwhelming evidence, the opposite is true: older adults who do not meet recommended activity levels due to their health condition are recommended to be as physically active as their abilities and conditions allow (WHO, 2020). This group of older adults could particularly benefit from individually adapted regular physical activity and exercise to prevent disease and disability progression and preserve autonomy and health-related quality of life (Moschny et al., 2011). Within this context, current evidence suggests that even physical activity participation below the recommended minimum level of 150–300 minutes per week of activity at a moderate-to-vigorous intensity is associated with positive health benefits in older adults (O'Donovan et al., 2017; Wen et al., 2011).

Several studies have modeled the effects of replacing sedentary time with time spent performing physical activity of any intensity on several outcomes (Mekary et al., 2013; Stamatakis et al., 2015). Among other findings, the results showed a reduction in mortality risk when total sitting time was replaced with physical activity of any intensity, including light-intensity activities such as standing (Physical Activity Guidelines Advisory Committee, 2018). However, no clear definition or consensus understanding of what signifies sedentary behavior has been available until recently (Tremblay et al., 2017), when the Sedentary Behaviour Research Network (SBRN) undertook a terminology project to develop a standardized definition of sedentary behavior. The resulting consensus definition defines sedentary behavior as "*any waking behavior characterized by an energy expenditure ≤ 1.5 metabolic equivalents (METs) while in a sitting, reclining, or lying posture*" (Tremblay et al., 2017).

Additional knowledge regarding how light-intensity physical activities contribute to health benefits as well as how physical activity and sedentary behavior relate is needed to better understand health outcomes and enable the provision of targeted physical activity advice. The prerequisite for this is a comprehensive and accurate assessment of physical activity and sedentary behavior.

Physical activity - a multidimensional behavior

The demand for a more holistic understanding of physical activity beyond the recommended moderate-to-vigorous activity intensity is not new. With the advent of technological devices (e.g., accelerometers) enabling the objective and continuous assessment of physical activity in real life (Ainsworth et al., 2015; Zijlstra & Aminian, 2007), several conceptual frameworks have been developed with the aim of emphasizing the multidimensionality of physical activity and providing guidance on its measurement (Bussmann & van den Berg-Emons, 2013; Pettee Gabriel et al., 2012; Rosenberger et al., 2019).

Pettee Gabriel et al. (2012) built their "*framework for physical activity as complex and multidimensional behavior*" around the global construct of human movement. They suggested that "*behavior that involves human movement*" can be conceptualized as *active* (e.g., physical activity) or *sedentary* and that the examination of the total behavioral profile of human movement requires the measurement of both types of behavior (Pettee Gabriel et al., 2012). Given the provisions of the SBRN's consensus definition, an evaluation of sedentary behavior requires, in addition to the quantification of energy expenditure, the assessment of body postures. Bussmann and van den Berg-Emons (2013) further highlighted that both physical activity and sedentary behaviors have relevant qualitative (i.e., activity type, body posture) and contextual (i.e., a person's environment) components that should be considered in addition to the total time spent in each behavior.

Insight into body postures and activity types may particularly enhance the understanding of differences or changes in habitual physical activity in older adults (van Schooten et al., 2018). Older adults primarily engage in light-intensity physical activity as part of everyday activities related to work, household chores, and leisure time. Thus, the performance of activities related to functional mobility (e.g., standing or walking) are a key construct of physical activity in older adults (Lindemann et al., 2014), which is consistent with van Schooten et al. (2018) suggestion that the general decline in total physical activity and increase in sedentary behavior with aging is the result of a decrease in walking activity and an increase in sitting time.

Accordingly, physical activity research has recently shifted to the study of whole-day physical activity, sedentary behavior, and sleep patterns and their relationships (Falck et al., 2022), as each moment of the daily 24-hour (24hr) cycle is spent in one of these behaviors, and each behavior is independently associated with a plethora of health outcomes. Numerous terms have been used to describe the 24hr cyclic patterns of physical activity, sedentary behavior, and sleep, including “movement behavior” (Ross et al., 2020), the “24hr activity cycle” (Rosenberger et al., 2019), “time-use behaviors” (Pedišić et al., 2017), and “time-use activity behaviors” (Falck et al., 2021), and no consensus has been reached on the terminology. According to Falck et al. (2021), the 24hr cyclic patterns of physical activity, sedentary behavior, and sleep can be dichotomized into wake-based behaviors (i.e., physical activity and sedentary behavior) and sleep-based behaviors (i.e., sleep). Together, they cover both ends of the approximately 24hr sleep–wake cycle, which is assumed to be regulated by an internal biological clock. Thus, physical activity, sedentary behavior, and sleep have a dynamic relationship with each other and with circadian regulation (Falck et al., 2021).

Circadian sleep–wake behavior

Most wake-based behaviors occur during a single wake phase of approximately 16 hours during the day, while sleep occurs during a single sleep phase of approximately 8 hours at night (Beersma & Gordijn, 2007). The temporal organization of the wake and sleep phases in relation to the time of day shows large interindividual variability, which is attributed to differences in the suprachiasmatic nucleus, the brain’s biological clock and the driver of circadian rhythms (Roenneberg et al., 2003). Circadian phenotypes can be summarized by the concept of chronotypes: individuals with an early beginning of their wake phase are referred to as morning types, individuals with a delayed beginning of their wake phase are referred to as evening types, and individuals with an intermediate beginning of their wake phase are referred to as neutral types (Roenneberg et al., 2003).

Changes in the circadian sleep–wake cycle occur as a function of normal aging and have been attributed to functional changes in the suprachiasmatic nucleus (Swaab et al., 1996; Witting et al., 1990). Among the most commonly reported changes is a phase shift in the sleep–wake cycle (Michel et al., 2015) constituting an earlier onset of both sleep- and wake-based behaviors (Roenneberg et al., 2015). Other changes include excessive daytime sleepiness and increased nocturnal awakenings (Landry & Liu-Ambrose, 2014), leading to a more fragmented sleep–wake cycle. People with dementia often experience exacerbated alterations in their sleep–wake cycles (Landry & Liu-Ambrose, 2014), with associated symptoms including nocturnal wandering and increased activity in the afternoon and evening, called the sundowning phenomenon (Ancoli-Israel et al., 1997; Boronat et al., 2019; Menegardo et al., 2019; Milán-Tomás & Shapiro, 2018; Venturelli et al., 2013; Volicer et al., 2001). Extreme disruptions in the sleep–wake cycle are typical in dementia and particularly in Alzheimer’s dementia, to the extent that they significantly increase family and caregiver burden and often lead to hospitalization or institutionalization of community-dwelling patients (Boronat et al., 2019; Kales et al., 2015; Neubauer et al., 2018; Okuda et al., 2019).

Construct underlying the assessment of physical activity

Consistent with Caspersen et al.'s (1985) definition of physical activity, the quantification of energy expenditure has traditionally been considered the construct underlying physical activity assessment (Ainsworth et al., 2015; Butte et al., 2012). Accordingly, physical activity is typically quantified in terms of estimating its metabolic cost by assessing the frequency and/or duration of activity at a given intensity over a given time period or within a given activity domain/type (e.g., number of bouts of activity > 10 minutes of moderate-to-vigorous intensity per day or total duration of gardening per week). Frequency, intensity, time/duration and type/domain of activity (often abbreviated as the FITT components) are commonly referred to as the four dimensions of physical activity. Although energy expenditure and physical activity are closely related, it is important to emphasize that they are not the same (Dowd et al., 2018). While activity-related energy expenditure may be the most important construct when examining physical activity and health in some populations, other aspects of physical activity, such as activities related to mobility and sedentary behavior, appear to be more important in older adults (Lindemann et al., 2014). Figure 1, an adapted version of the 24hr physical behavior construct (Stevens et al., 2020) developed by the Prospective Physical Activity, Sitting and Sleep consortium (ProPASS), shows one way of structuring physical activity that takes into account its multidimensionality and its association with sedentary behavior and sleep. Unlike the original by Stevens et al. (2020), the presented approach includes a separate dimension for the temporal aspects of physical activity following the framework of Falck et al. (2021), and an additional dimension for the context (e.g., where, and with whom) as intended by Bussmann and van den Berg-Emons (2013) in which physical activity, sedentary behavior, and sleep occur. It is important to note that the temporal dimension is not limited to 24hr cycles, although these are of most relevance to this thesis. While metabolic measures and the estimation of activity-related energy are primarily understood as the quantitative aspects of physical activity, the other dimensions of physical activity can also be quantified. Hence, frequency, transition between bouts and (bout) duration are included as cross bracing aspects, that span across dimensions. The bout duration provides information about the time spent on different activity intensities, types, or postures in uninterrupted periods; meaningful bout length could be different for the different dimensions and their components (Stevens et al., 2020). Transition between bouts might be most applicable for the individual postural components as they do not exist separately and do not merge abruptly in real-life; the transition between activity types and postures may hold important context.

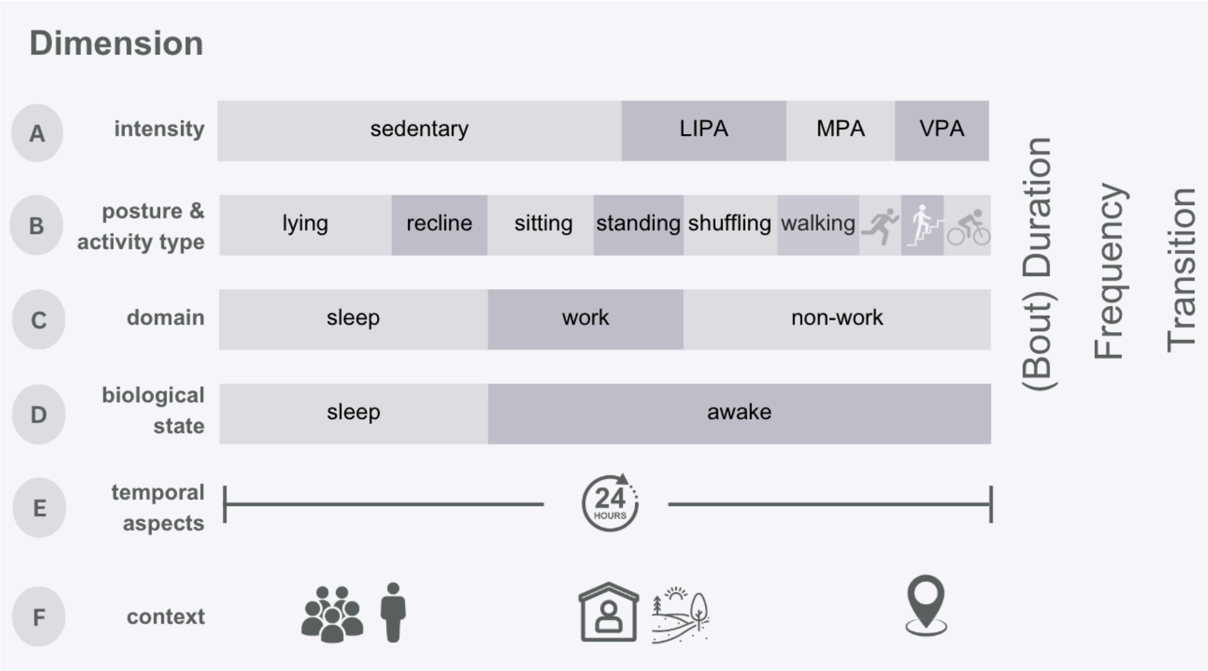

Figure 1: Adapted version of the ProPASS 24-hour (24hr) physical behavior construct; including a separate dimension for the temporal aspect of physical activity (PA) and an additional context dimension; A: The basic intensity based dimension of the 24hr PA construct stratified on sedentary behavior (SB), light physical activity (LIPA), moderate physical activity (MPA) and vigorous physical activity (VPA); B: Posture- and activity type-based dimension; C: Domain- based dimension (i.e., domain in which PA and SB occur); Dimension D: Differentiates the biological states of sleep and wakefulness. Dimension E: temporal aspects of PA and SB such as the time of day; F: Context (e.g., where and with whom). ProPASS – Prospective Physical Activity, Sitting and Sleep consortium.

Adopting this broader understanding of physical activity as the underlying construct of physical activity assessments could facilitate a deeper understanding of health outcomes and the provision of personalized physical activity advice for older adults. This raises the question of suitable measurement methods that can be used for scientific purposes as well as in clinical practice to monitor changes and evaluate intervention outcomes.

Physical activity assessment tools

Two methodological approaches are employed to assess physical activity: subjective and objective methods (Ainsworth et al., 2015; Strath et al., 2013). Subjective methods typically rely on an individual's self-report either by recording activities and contextual information as they occur (e.g., activity logs, ecological momentary assessment) or by recalling previous activities and context (e.g., surveys, questionnaires, diaries). Objective methods include all wearable monitors (e.g., pedometers, accelerometers, heart rate monitors, complex multi-sensor systems) that directly measure one or more biological signals, such as acceleration or heart rate (Ainsworth et al., 2015; Strath et al., 2013).

Until recently, physical activity was primarily assessed by self-report methods, particularly questionnaires. Because they are inexpensive and easy to administer, questionnaires have been a frequent method of choice in epidemiological and population-wide studies (Ainsworth et al., 2015; Warren et al., 2010). Questionnaire-based data have contributed substantially to the current understanding of physical activity and health risks and continue to constitute a large portion of the evidence for physical activity guidelines. However, questionnaires are not without considerable limitations, particularly in older adults. Although validation studies have shown questionnaires to have strong correlations and agreement with other construct criteria measures for vigorous-intensity physical activity, they are generally less accurate for light- and moderate-intensity activities (Strath et al., 2013). Furthermore, the challenge of recalling all physical activity details (e.g., frequency, duration, and intensity in one or more domains and over a specific period) can lead to overestimation or underestimation of physical activity, particularly physical activity relating to activities of daily living (Allet et al., 2010; Durante & Ainsworth, 1996). This dependency on respondents' memory limits the usability of self-report measures in older adults with cognitive impairment (e.g., dementia). In addition, self-report tools are susceptible to social desirability bias, or the overreporting of good behaviors (Kowalski et al., 2012).

Physical activity in patients with dementia is often evaluated observationally by clinicians and nursing staff during their work shifts or through proxy-based assessments. Though observation is considered an objective assessment method, it relies on the rater's subjective impression, which has been shown to be susceptible to overestimation and underestimation (King-Kallimanis et al., 2010). Subjectivity and rater-dependence in psychopathometric assessment instruments limit their clinical use for tailoring and evaluating intervention approaches (Halek & Bartholomeyczik, 2012). Given that common behavioral symptoms in dementia, including disruptions in circadian motor behavior, affect mobility-related activities (e.g., high levels of sedentary behaviors, wandering during sundowning or nighttime), this group of individuals could particularly benefit from an accurate and long-term assessment of physical activity and an individualized treatment strategy derived from it.

In contrast to subjective questionnaire-based methods, objective sensor-based measurement systems have the potential to capture physical activity parameters with higher levels of validity and reliability (Dowd et al., 2018). Objective methods of directly assessing physical activity range from simple to complex sensor systems (Arvidsson et al., 2019). Accelerometers have been incorporated into a series of devices (e.g., pedometers, actigraphs, and hybrid motion sensors) that are frequently used in biomedical research to assess physical activity (Ainsworth et al., 2015; Zijlstra & Aminian, 2007). Accelerometers have primarily been employed to quantify total daily physical activity, classify activity intensity, and estimate physical activity-induced energy expenditure based on activity counts (Liu et al., 2022).

Pedometers represent the simplest method of objectively monitoring physical activity (Rao, 2019). While past models included a mechanical sensor to detect steps, recent models additionally employ on-board algorithm-based processing of acceleration signals to identify steps (Ainsworth et al., 2015). Because pedometers are limited to the assessment of step count and related parameters (e.g., steps/minute, estimated walking distance), they cannot provide qualitative information, such as the type of activity (except for walking) or body posture (Ainsworth et al., 2015), or information on physical activity patterns (e.g., rest–activity cycle). Other accelerometer-based devices continuously record the acceleration of the body or body parts in gravitational units in one or more orthogonal planes (Ainsworth et al., 2015). Algorithms are then utilized to process the raw acceleration data (Westerterp, 2014). A popular algorithmic approach is to transform raw accelerations into activity counts per epoch (e.g., 60 seconds) (Strath et al., 2013). By applying device- and population-specific thresholds from calibration studies, physical activity outcomes such as estimated energy expenditure or physical activity intensity can be derived (Ainsworth et al., 2015; Strath et al., 2013). This type of analysis (also known as actigraphy) is frequently used in sleep medicine for the ambulatory assessment of circadian rest–activity cycles and to study the relationship between physical activity behavior and sleep. However, analyzing physical activity based on counts does not elicit information regarding physical activity type or posture (van Schooten et al., 2018). Hybrid motion sensors, devices that integrate a gyroscope or rotation rate sensor and magnetometer in addition to the accelerometer, were developed to address this limitation. Algorithmically combining the acceleration signals with signals from the additional sensors enables the assessment of qualitative components of physical activities, such as the type of activity (e.g., walking, cycling), body posture (e.g., lying, sitting, standing), and postural transitions (Ghosh et al., 2018; Lindemann et al., 2014).

However, a gold standard for the assessment of physical activity behavior using wearable motion sensors has not been established. Challenges remain in comparing results between studies due to differences in technical features, device placement, and methods of analyzing and reporting data. Difficulties also exist when comparing findings from studies using device-based measures with findings from studies using self-report measures.

Circadian aspects of physical activity: assessment and analysis

The circadian aspects of physical activity have traditionally been assessed to study sleep and circadian rhythms as well as their age- and disease-related alterations (e.g., circadian rhythm disturbances in dementia). Wrist-worn actigraphy is the most commonly applied method in research and sleep medicine to determine measures of sleep quality (e.g., sleep duration and pattern) and circadian rhythm based on the rest–activity cycle (Morgenthaler et al., 2007). The most frequently employed techniques for analyzing rest–activity cycles are cosine-type modeling and non-parametric approaches. The latter have been developed to accommodate for the fact that human rest–activity cycles generally do not follow a simple cosine curve (Van Someren, 2011). Thus, important information regarding activity patterns might remain undiscovered due to the lack of fit with cosine functions, particularly when analyzing populations with certain diseases (Van Someren, 2011). With non-parametric approaches, metrics based on the level and variability found in a time series of activity count recordings are calculated (Van Someren et al., 1996; Witting et al., 1990). Non-parametric measures of the timing and level of the peak and trough of the rest–activity cycle include the average number of activity counts during the ten most active hours, reflecting the peak activity level, and the average number of activity counts during the five least active hours, reflecting the level of activity during rest (Van Someren et al., 1996; Witting et al., 1990). Intra-daily variability and inter-daily stability are the non-parametric indicators of fragmentation in the rest–activity cycle within a day and between days, respectively (Witting et al., 1990). Intra-daily variability provides an indication of the frequency and extent of transitions between rest and activity, while inter-daily stability indicates the strength of coupling between the rest–activity cycle and external zeitgebers (i.e., environmental cues with a supposedly stable 24hr pattern such as lighting conditions during the day and night) (Van Someren, 2011; Witting et al., 1990).

As highlighted above, alterations in the circadian rest–activity cycle occur as a function of age and are typically exacerbated in dementia. Individualized implementation and evaluation of pharmacological and non-pharmacological treatments are key aspects of acute dementia care (Kales et al., 2015); however, a specific assessment of patients' circadian physical activity behavior, which should be a prerequisite for certain treatment approaches, is not commonly applied in clinical practice. A clinically applicable method of evaluating the circadian aspects of functional mobility-related and sedentary behaviors could be valuable for assessing circadian motor disruptions (Zijlstra & Aminian, 2007) and enabling individualization of treatment strategies. However, few approaches have addressed the circadian aspects of mobility-related behavior in community-dwelling older adults and patients with dementia.

Physical activity monitoring-based interventions in older adults

Physical activity interventions often include approaches based on theoretical models, primarily the social cognitive theory (SCT), that address behavior change techniques (BCTs) (Mercer et al., 2016; Young et al., 2014). Of the constructs of SCT, self-efficacy and self-regulatory strategies, including goal setting, appear to be the core components positively related to physical activity behavior (Young et al., 2014) and mobility (Giannouli et al., 2019). Other BCTs often applied in physical activity promotion interventions that are particularly relevant in older adults include feedback, limitation of barriers, educational aspects (e.g., health literacy, raising awareness of the benefits of physical activity, minimizing perceived risks), and improving environmental and financial access to physical activity opportunities (Franco et al., 2015; Mercer et al., 2016; Seinsche et al., 2020).

Wearable activity monitors and their user interfaces employ several BCTs that have been shown to increase physical activity, including goal setting, self-regulation, and social support, which are found in most devices, and self-efficacy (e.g., planning, consequences, knowledge), which has been incorporated into some devices (Mercer et al., 2016). Activity monitors are thus a promising tool in interventions aiming to enhance physical activity in older adults (Mercer et al., 2016). The body of research evaluating interventions that employ motion sensor technology to enhance physical activity has rapidly grown over the past decade. Several systematic reviews and meta-analyses have investigated the effectiveness of interventions using wearable activity monitors in different populations (Armstrong et al., 2019; Baskerville et al., 2017; Braakhuis et al., 2019; Bravata et al., 2007; Brickwood et al., 2019; Chaudhry et al., 2020; Cooper et al., 2018; Davergne et al., 2019; de Vries et al., 2016; Funk & Taylor, 2013; Hannan et al., 2019; Hodkinson et al., 2019; Kanejima et al., 2019; Kirk et al., 2019; Larsen et al., 2019, 2022; Lewis et al., 2015; J. Y. W. Liu et al., 2020; Lynch et al., 2020; Mansi et al., 2014; Oliveira et al., 2019; Qiu et al., 2015, 2018; Rintala et al., 2018; Stephenson et al., 2017; Vaes et al., 2013). The findings vary widely depending on the specific physical activity outcome (e.g., overall physical activity, moderate-to-vigorous physical activity, sedentary time) and population (e.g., adults ≥ 18 years, older adults, adults with specific conditions) investigated. Overall, interventions incorporating physical activity monitors appear to have a small to moderate positive effect on physical activity in general adult populations (Larsen et al., 2022; Physical Activity Guidelines Advisory Committee, 2018) and a moderate effect in older adults (Cooper et al., 2018; Larsen et al., 2019; Liu et al., 2020; Oliveira et al., 2019), older former health care patients (Braakhuis et al., 2019), and older adults with chronic obstructive pulmonary disease (Armstrong et al., 2019; Qiu et al., 2018).

While the effects of motion sensor-based interventions in older adults have been investigated, the existing body of evidence has not been systematically reviewed from the perspective of intervention characteristics, such as type of intervention, frequency and type of feedback, and type of goal setting. As stated above, goal setting is a key component of physical activity interventions. Behavioral research on goal setting suggests that goals should be established with consideration of the individual's previous and current performance and ability level (Kwasnicka et al., 2020) to optimize physical activity engagement. Inactive older adults and older adults with chronic conditions may particularly benefit from personalized goal setting to enhance physical activity participation. Motion sensors can provide objective and detailed data (e.g., on mobility-related behavior, temporal parameters) regarding older adults' real-life physical activity behavior (Geraedts et al., 2021) that can be utilized to tailor interventions by enabling the analysis of individual needs and the setting of appropriate goals. However, how and to what extent this type of analysis is already applied in motion sensor-based interventions and the feasibility (e.g., adherence) of these interventions remain unclear. When evaluating a tool's applicability in clinical practice, such information is highly relevant.

Objectives of the thesis

The aim of this thesis is to evaluate the use of motion sensor-based approaches to assess and monitor physical activity as input into interventions for older adults, specifically in geriatric health care settings. This primary objective is pursued by addressing the following research questions:

a) How do the outcomes of different methodological approaches to assessing physical activity and sedentary behavior differ, and what are the implications for their clinical applicability?

b) Are circadian aspects of mobility-related behavior, such as the time of day of peak gait activity, related to the self-reported chronotype of older adults?

c) Are differences in circadian aspects of mobility-related behavior of patients with dementia in an acute psychiatric care setting related to their clinical characteristics?

d) How is motion sensor-based monitoring of physical activity currently used to guide and personalize physical activity interventions in geriatric health care?

To answer these questions, this thesis presents the following: a report comparing three assessment methods for quantifying physical activity (**Chapter 2**), a proof-of-concept study evaluating the use of body-worn motion sensors to assess circadian aspects of mobility-related behavior in community-dwelling older adults (**Chapter 3**), a paper exploring how circadian aspects of mobility-related behavior relate to clinical characteristics in acute dementia care (**Chapter 4**), and a scoping review of the components and clinical applicability of physical activity monitoring-based interventions in geriatric patients (**Chapter 5**). The final sections of this thesis (**Chapters 6** and **7**) will provide a general discussion of the thesis' findings, an outlook on the direction of future research as well as clinical practice and the final conclusion.

Chapter 2

Assessment of physical activity

Quantifying Habitual Physical Activity and Sedentariness in Older Adults – Different Outcomes of Two Simultaneously Body-Worn Motion Sensor Approaches and a Self-Estimation

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Abstract: Applicable and accurate assessment methods are required for a clinically relevant quantification of habitual physical activity (PA) levels and sedentariness in older adults. The aim of this study is to compare habitual PA and sedentariness, as assessed with (1) a wrist-worn actigraph, (2) a hybrid motion sensor attached to the lower back, and (3) a self-estimation based on a questionnaire. Over the course of one week, PA of 58 community-dwelling subjectively healthy older adults was recorded. The results indicate that actigraphy overestimates the PA levels in older adults, whereas sedentariness is underestimated when compared to the hybrid motion sensor approach. Significantly longer durations (hh:mm/day) for all PA intensities were assessed with the actigraph (light: 04:19; moderate to vigorous: 05:08) when compared to the durations (hh:mm/day) that were assessed with the hybrid motion sensor (light: 01:24; moderate to vigorous: 02:21) and the self-estimated durations (hh:mm/day) (light: 02:33; moderate to vigorous: 03:04). Actigraphy-assessed durations of sedentariness (14:32 hh:mm/day) were significantly shorter when compared to the durations assessed with the hybrid motion sensor (20:15 hh:mm/day). Self-estimated duration of light intensity was significantly shorter when compared to the results of the hybrid motion sensor. The results of the present study highlight the importance of an accurate quantification of habitual PA levels and sedentariness in older adults. The use of hybrid motion sensors can offer important insights into the PA levels and PA types (e.g., sitting, lying) and it can increase the knowledge about mobility-related PA and patterns of sedentariness, while actigraphy appears to be not recommendable for this purpose.

Keywords: actigraphy; hybrid motion sensors; physical activity; sedentariness

1. Introduction

Sedentariness negatively impacts the health of older adults e.g., risk of chronic diseases, falls, and reduced quality of life [1–6]. Applicable and accurate assessment methods are required for a clinically relevant quantification of habitual physical activity (PA) levels and sedentariness in older adults.

Questionnaires, activity logs, or diaries are often used as self-estimations of PA levels. These are cheap instruments that allow for assessing a large number of participants [7], but they often fail to address sedentariness as well as activities with light intensity [8,9]. A recall bias, especially regarding activities of daily living and over- or underestimation of PA, further limits the use of self-estimations in older adults [10,11].

Body-worn motion sensors allow for continuously monitoring and objectively quantifying PA [12] in terms of frequency, duration, and intensity, over long periods (e.g., days, weeks, month) [8]. A common sensor-based approach for assessing PA is actigraphy and the quantification of PA in counts per epoch [8,13]. Actigraphs are small, watch-like devices, which allow for an objective assessment of PA with minimal obtrusiveness [8]. Based on device- and population specific thresholds of the actigraphy data, the PA-levels are classified into sedentary, light, moderate, and vigorous intensities [8]. However, the detection of sedentariness based on an analysis of activity counts from wrist-worn actigraphy appears to be challenging. In a previous trial, a sensitivity of only 53% in the detection of sedentariness in a sample of healthy adults during different activities was obtained [14]. The authors concluded that the inter-person variability in wrist movements during sedentariness might result in misclassification [14]. Furthermore, actigraphy and analysis based on counts does not allow for quantifying the type of PA [15].

Recently used body-worn hybrid motion sensors, incorporating accelerometers, gyroscopes, and magnetometers allow for analyzing the type of PA (e.g., sitting, walking) as well as detecting different postures (e.g., seated, standing) and postural transitions [16].

Current methodological reviews discuss the (dis-)advantages of quantifying PA levels and sedentariness based on counts and the PA type [8,9,17]. However, there is no gold standard for the assessment of habitual PA yet, and the results from a comprehensive comparison of self-estimated PA levels and different sensor approaches to quantify differences in older adults are lacking. To be able to relate results on PA of different approaches, the aim of this study is to compare habitual PA levels and sedentariness assessed with two simultaneously body-worn motion sensors: (1) an actigraph, (2) a hybrid motion sensor approach and a PA questionnaire in healthy older adults.

2. Materials and Methods

This investigation was part of the ChronoSense project—a cross-sectional trial to investigate the use of body-worn motion sensors to quantify circadian chronotypes in older adults (DRKS00015069, German clinical trials register). The Ethics Committee of the German Sport University Cologne approved the study protocol (registration number 156/2017).

2.1. Participants

The participants were included to the project based on the following criteria: community-dwelling, age of 65 years or older, a score on the Mini-Mental Status Examination (MMSE) ≥ 24 [18,19], subjective health (self-reported), and written informed consent to the study procedures. Persons with any acute or severe mobility impairment, cardiovascular disorder, cognitive disorder, or neurological disease (assessed with the Functional Comorbidity Index (FCMI) [20]), which could interfere with functional mobility, were excluded.

The recruitment strategy included sending out emails with information brochures to local senior citizens' networks and employees of a large municipal association in the Rhineland region in Germany, and word of mouth referrals. Furthermore, persons who expressed interest in participating in studies of the Institute of Movement and Sport Gerontology in the past were invited by email or telephone call. It was ensured that these test persons had not participated in any scientific experiment in the previous year.

2.2. Instruments

The self-estimation of PA levels was assessed while using the German Physical Activity Questionnaire 50+ (GPAQ 50+) [21], a self-administered questionnaire assessing older adults' PA level per week. The participants were asked to estimate for how many hours they performed certain activities on average per week during the last four weeks. The questionnaire covers activities related to the categories household, gardening, leisure time, exercising, and voluntary work. Each of the activities is assigned to a metabolic equivalent of task (MET) [22]. The overall score of the GPAQ 50+ is based on the quantification of the activity level in MET hours: activity duration [h/week] × MET or the energy expenditure: activity duration [h/week] × MET × body weight [kg]. The GPAQ 50+ was administered prior to the sensor-measurements. Therefore, the self-estimated PA levels refer to an average week during the four weeks before and the sensor measurement period.

The wrist-worn MotionWatch 8 (Camntech, Cambridge, UK) was used for the actigraphy-based assessment of PA levels. The MotionWatch 8 (MW8) integrates a triaxial accelerometer (sample frequency up to 11 Hz), a light sensor, and an event marker button. The MW8 allows data collection for up to three months. The participants wore it on the wrist of their non-dominant hand. The data were collected in the triaxial mode with an epoch length of 60 s.

The Dynaport Move Monitor+ (McRoberts, Den Haag, NL) was used as hybrid motion sensor. The Dynaport Move Monitor+ (MM+) consists of a triaxial accelerometer, a triaxial gyroscope, a triaxial magnetometer, a barometer, and a temperature sensor. Sample frequency of the accelerometer and gyroscope was 100 Hz. The MM+ allows for a collection of data for up to seven consecutive days. The MM+ was attached to the participants' lower back, approximately 3 cm right to the fifth vertebra of the lumbar spine (L5) using waterproof self-adhesive fixing foil (Opsite Flexifix, Smith and Nephew, London, UK), enabling a consistent recording of PA. The participants were asked not to swim, have a sauna or take a bath during the measurement period. Furthermore, the participants were asked to wear both sensors continuously during the measurement period. Only sensor data of participants with six or more complete measurement days were included to ensure an assessment of habitual PA levels.

2.3. Data Collection

Sensor-data were collected over the period of one week, aiming to monitor the participants' PA over 24 h without interruption on all seven days of the week. The measurement period started with an individual appointment in the laboratory in which the GPAQ 50+ was administered and the participants were equipped with the two sensors. Furthermore, a general questionnaire assessing the participants living situation (e.g., material status, income) as well as the health status (e.g., number and kind of chronic diseases) was administered. The sensors were removed from the participants' bodies and special incidents during the measurement period, possibly interfering with the participants' PA (e.g., acute illness) were noted, during a second appointment after the end of the measurement period. As the aim of the study was to compare habitual PA levels, the participants were asked to estimate whether the measurement period was usual in terms of their habitual PA. If they considered the measurement period as unusual, the participants were asked to specify whether their PA was higher or lower than usually. Finally, the participants indicated whether or not they had removed one or both the sensors during the measurement period and specified the period if this was the case.

2.4. Data Processing

The sensor data were processed while using the respective manufacturer's own algorithms. The output of the MW8 (DayAnalysis, CamNtech, Fenstanton, UK) includes total counts per 60 s epochs. Landry and colleagues [23] used concurrent measurements of actigraphy and indirect calorimetry during activities of daily living (e.g., lying, sitting, standing, walking) to validate the use of MW8 activity counts for dissociating sedentary, light, and moderate to vigorous PA in healthy older adults. The optimal cut-points for sedentary (<1.5 METs), light (1.5–3.0 METs) and moderate to vigorous (>3 METs) intensity (as in the Compendium of Physical Activities [22]) were determined from Receiver Operating Characteristic (ROC). For a full description, see Landry and colleagues [23]. The derived cut-points were as follows: for sedentariness ≤178.5 counts per minute with a sensitivity of 78%, specificity of 70%, and an accuracy of 71%, and for moderate to vigorous intensity ≥562.5 counts per min. with a sensitivity of 40%, a specificity of 90%, and an accuracy of 69%. Light PA was determined as the activity level between the boundaries for sedentariness and moderate to vigorous PA (i.e., between 178.5–562.5 counts per min.). In the present study, the cut-points that were established by Landry and colleagues [23] were used to determine activity intensity. Average counts per minute were calculated for the description of overall PA level.

The output of the MM+ included PA type (walking, stair walking, cycling, shuffling, standing, sitting, and lying) plus an additional category not-worn, corresponding MET-values, activity duration, and number of steps per 60 s epoch. Van Hees and colleagues [24] developed a model for the analysis of MM+ (MoveMonitor, McRoberts, The Hague, NL, USA) data that combines the type of activity and its intensity for the prediction of energy expenditure. A standardized protocol comprising lying, sitting, standing, and walking was used to determine the best-fit linear equations between movement intensity (as assessed with an accelerometer) during each type of activity, and activity related energy expenditure (as assessed via indirect calorimetry). A next step then determined for each second the detected type of activity and the equation to be used for estimating energy expenditure. The resulting model for prediction of energy expenditure was validated in a respiration chamber. Within subjects, the variation in energy expenditure explained by the model was 81%. Between subjects, the prediction model explained 58% to 70% of the variation in energy expenditure. For the description of PA types, the total durations of PA types and total number of steps were calculated. To determine PA with light, moderate to vigorous intensity and sedentariness for the MM+ the same MET-based thresholds that Landry and colleagues [23] used to calibrate the cut-points for the MW8 were used: <1.5 METs for sedentary, 1.5–3.0 METs for light, and >3 METs for moderate to vigorous PA.

Self-estimated durations for light and moderate to vigorous activity were assessed by summing up the reported durations for each intensity. The durations of sedentariness cannot be derived from the GPAQ 50+. The same MET-based thresholds as the MM+ were applied to determine PA with light and moderate to vigorous intensity.

The average durations per day of light and moderate to vigorous PA intensities, as well as sedentariness were calculated for all three assessment methods.

2.5. Statistical Analysis

Statistical analysis was conducted with IBM SPSS Statistics 26.0 for Windows (International Business Machines, Armonk, NY, USA). Extreme values of more than three times the interquartile distance were identified using boxplots and excluded from further analysis. Normal distribution was examined with the Kolmogorov Smirnov test after the exclusion of extreme values. Analyses of variance with repeated measurements (ANOVAs) or Friedman-tests were performed to assess differences in PA with light and moderate to vigorous intensity between the three methods. If no sphericity was given, the Greenhouse–Geisser correction was used.

Significant differences were examined with the Bonferroni post hoc test. As sedentariness was not assessed with the GPAQ 50+, differences in the assessment of sedentariness between the MW8 and the MM+ were examined while performing a *t*-test for paired samples or the Wilcoxon-Test. An alpha <0.05 was considered to be statistically significant.

3. Results

3.1. Participants

A total of 118 community-dwelling older adults were screened for eligibility. Twenty-three persons did not confirm to participation, 10 persons did not fit the inclusion criteria. Data collection was initiated with 85 persons. Two participants were excluded due to acute illness during the measurement period. The data of one participant who indicated that he was less active than usual during the measurement period were excluded from analysis. Nine participants had to be excluded due to missing data of the MW8 and six due to missing data of the MM+. Eight participants were excluded, because MM+ data of less than six complete measurement days were available (mostly due to battery issues). One participant did not wear the MM+ according to the instructions and was excluded. Finally, data of 58 participants were analyzed. Table 1 shows their characteristics.

Table 1. Sample characteristics and physical activity results of the German Physical Activity Questionnaire 50+, MotionWatch8, and the Move Monitor+.

	n (%)	Mean	SD	Min	Max
N	58				
Female	35 (60)				
Age		71.6	5.0	64	83
BMI		25.8	4.2	20	38
MMSE		28.8	1.3	25	30
Number of Diseases		2.1	1.4	0	7
FCMI		1.4	1.3	0	5
Physical Activity					
German Physical Activity Questionnaire 50+					
activity level [MET hours/day]		145.2	88.9	22	423
energy expenditure [kcal/week]		11193.6	7178.7	2903	38747
MotionWatch 8					
counts/ minute		317.5	82.0	135	563
Move Monitor +					
activity duration [hh:mm/day]					
lying		09:57	01:31	07:28	14:56
sitting		08:47	01:47	04:52	12:59
standing		02:55	00:45	00:57	04:35
shuffling		00:27	00:07	00:10	00:47
walking		01:50	00:34	00:41	03:02
other activities*		00:04	00:09	00:00	00:59
steps / day		9816.3	3539.6	3700	18321

BMI—Body Mass Index; FCMI—Functional Comorbidity Index (0–18 points; low scores indicate good functioning); h—hour; Kcal—kilocalories; m—minute; MET—Metabolic equivalent of task; MMSE—Mini Mental State Examination; SD—standard deviation; *—summation of total activity durations for cycling and stair walking.

3.2. Results on Physical Activity

Table 1 presents the results of the PA assessment. The average measurement duration of the MW8 was seven days. All of the participants reported to have worn the MW8 continuously over the measurement period. The average measurement duration of the MM+ was 6.9 days. Two participants (3.4%) reported to have reattached the MM+ once during the measurement period.

3.3. Physical Activity Intensities

Figure 1a,b show the average durations of PA with light and moderate to vigorous intensities for the GPAQ 50+, MW8, and MM+ in hours per day. Figure 1c illustrates the duration of sedentariness that was assessed with the MW8 and the MM+. Two extreme values in the duration of PA with light activity assessed with GPAQ 50+ and the MM+ were identified and excluded from data analysis. Significant differences (p ≤ 0.01) in the durations of all PA intensities were found between all of the assessment methods, except for PA with moderate to vigorous intensity between the MM+ and the GPAQ 50+ (p = 0.412).

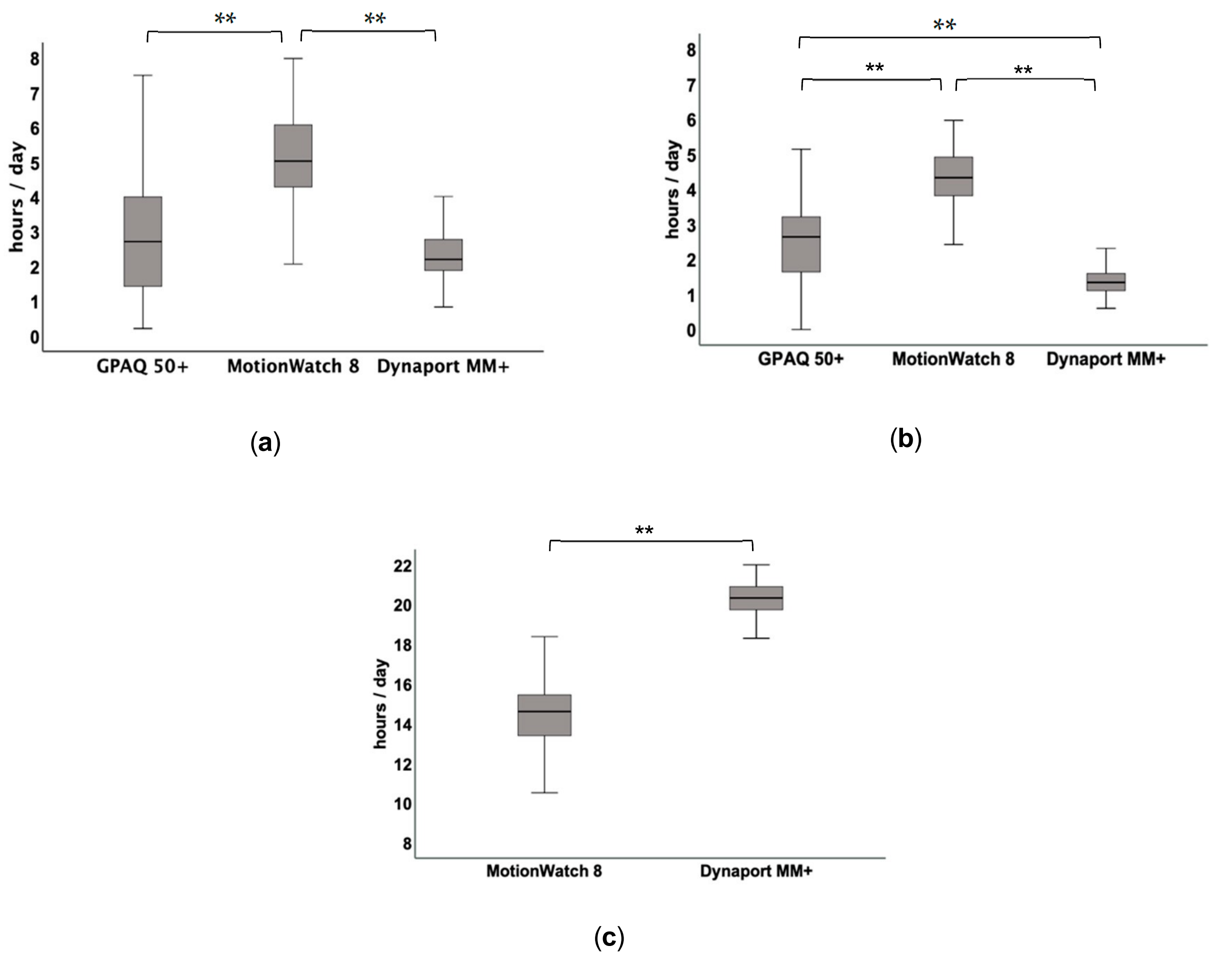

Figure 1. Box-plot illustration of German Physical Activity Questionnaire 50+, MotionWatch8 and MoveMonitor+ derived total duration [hour/day] of physical activity intensity and sedentariness:
(**a**) moderate to vigorous intensity (Friedman-test with Bonferroni post-hoc test); (**b**) light intensity (repeated measurement analysis of variance with Bonferroni post-hoc test); and, (**c**) sedentariness (t-test for paired samples). ** $p \leq 0.01$.

4. Discussion

The aim of this study was to compare habitual PA levels and sedentariness assessed with two simultaneously body-worn motion sensors, (1) an actigraph, (2) a hybrid motion sensor approach and a PA questionnaire in healthy older adults.

Longer durations for all PA intensities were assessed with the wrist-worn actigraph. Moreover, actigraphy-assessed durations of sedentariness were much shorter as compared to the durations that were assessed with the hybrid motion sensor. These results indicate that an actigraphy-based assessment of PA leads to an overestimation of older adults' habitual PA levels when compared to a self-estimation and a body-worn hybrid motion sensor, as well as an underestimation of sedentariness when compared to a hybrid motion sensor.

The significantly longer durations of light (02:55 hh:mm/day), moderate to vigorous intensity (02:47 hh:mm/day) between the MW8 and the MM+, and the differences in durations of sedentariness (05:43 hh:mm/day) might be due to differences in sensor placement and data analyses. In case of the MW8, accelerometer raw data is analyzed to counts per epoch, which allows for assessing the presence or absence of activity and its intensity. Energy expenditure is predicted solely based on intensity, as determined from counts. Furthermore, the wrist-placement of the MW8 only allows for an assessment of hand and upper-limb activity. Information on body posture, acceleration, or movement direction and, thus, on mobility-related PA cannot be obtained with this method [25]. The analysis of the MM+ data and its lower-back placement provide, next to activity intensity and steps, information on the type of PA (e.g., shuffling, walking) and, thus, enables the assessment of mobility-related PA. The combination of information on the type of PA and its intensity is assumed to improve the prediction of energy expenditure, especially in sedentariness [24].

Previous findings also indicated that actigraphy-based assessment and an analysis based on activity counts lack sensitivity in the detection of sedentariness [8] and that the accurate assessment of sedentariness, that is based on wrist-worn accelerometer data, is challenging [14]. Nevertheless, the attachment of accelerometers to the hip/lower back has also been considered critical, due to problems with compliance and possible measurement error that is induced by changes in the sensor placement on the body [8,17]. In the trial of van Schooten and colleagues [15], the participants wore the MM+ in a belt around the hip, requiring them to remove it during (un-) dressing and activities, such as showering. In the present trial, we chose to attach the MM+ with waterproof, self-adhesive foil to the participants' bodies to increase wearing times to a complete 24/7 schedule [25]. This attachment allows for also wearing the sensor during activities of daily living, like showering, makes it more difficult for the participants to take off the sensor themselves, and less likely to forget the reattachment of the sensor, as indicated by the low number of participants (n = 2) who reattached the sensor.

When comparing the MW8 and the MM+ regarding feasibility, the results indicate a somewhat better feasibility of the wrist-worn MW8 as compared to the lower back worn MM+ in the investigated sample of active healthy older adults. However, the results regarding the assessed durations of PA intensities and sedentariness and the detailed analysis options indicate the MM+ as the superior choice to the MW8.

The self-estimated durations for PA with light and moderate to vigorous intensity were significantly shorter when compared to MW8 and when compared to the MM+, the self-estimated durations of moderate to vigorous PA were significantly longer. Though these results seem to indicate that the GPAQ 50+ might be a useful tool for estimating durations of moderate to vigorous PA, the self-estimation of PA levels will always rely on the participant's memory ability and it does not allow for a continuous quantification of habitual PA levels [8,9]. Therefore, its suitability appears to be limited, especially in the investigation of PA levels in patients with cognitive disabilities or the investigation of circadian aspects of PA.

This is the first study comparing the PA levels and sedentariness that were assessed with a simultaneously wrist-worn actigraph and a hybrid motion sensor-based approach. Large differences in the durations of PA intensities and sedentariness were observed between both sensor-based approaches. Actigraphy is based on the assessment of wrist movements and an analysis in counts per minute. Previous results indicate that an analysis based on wrist-worn actigraphy lacks sensitivity, especially in the detection of sedentariness [14]. Regarding the MM+, accuracies of 91–99% in the detection of sitting, and 97% in the detection of lying are reported [26]. Given these results, it can be assumed that wrist-worn actigraphy underestimates the durations of sedentariness in older adults. According to the Sedentary Behavior Research Network (SBRN), any waking behavior characterized by an energy expenditure ≤1.5 METs while in a sitting, reclining, or lying posture refers to sedentariness [27]. An analysis solely based on counts per minute does not allow for an evaluation of PA and sedentariness according to this definition [15]. Furthermore, more detailed information on sedentariness (activity type, frequency of postural shifts) is clinically relevant in understanding health outcomes [8,16]. Along with the growing evidence on sedentariness as an independent risk factor for diseases [8] and mobility-related PA as an important factor in the maintenance of health status and independent functioning [12,28], methods to quantify PA should be able to differentiate between sedentariness and mobility-related PA. Hybrid motion sensors, like the MM+, can provide this kind of information and should, therefore, be considered superior to actigraphy in the assessment of older adults' habitual PA and especially sedentariness.

According to the guidelines of the American College of Sports Medicine (ACSM), older adults should achieve a PA level of 7.5 to 12.5 MET hours per week to maintain health status [29]. The investigated sample of older adults exceeds the ACSM recommendations, especially according to the self-estimation (GPAQ 50+ activity level of 145.2 MET hours). This difference might be due to the fact that the amount of PA that is recommended by the ACSM is in addition to routine activities of daily living (e.g., self-care, cooking, casual walking, shopping) [29]. The PA levels that were assessed with the GPAQ 50+, however, include these activities. The sensor-based assessments showed similar PA levels to those that were previously recorded in comparable samples. An average of 317.5 counts per minute assessed with the MW8 is in line with the results that were reported by Landry and colleagues (321.4 and 276.9 MW8 counts per minute; obtained from two simultaneously worn MW8s) [23]. Regarding the results of the MM+, an analysis of PA type showed a total duration of 09:57 hh:mm/day for lying, 08:47 hh:mm/day for sitting, 02:55 h for standing, 00:27 hh:mm/day for shuffling, and 01:50 hh:mm/day for walking per day. Van Schooten and colleagues [15] reported similar durations for the PA types. They observed a total duration of 09:48 hh:mm/day for lying, 09:46 hh:mm/day for sitting, 02:58 hh:mm/day for standing, 01:10 hh:mm/day for walking, and 00:12 hh:mm/day for cycling in a sample of healthy older adults aged 71 to 80 years.

There are methodological limitations regarding this study. First, of the initially 85 included persons, only the data of 58 participants were included in the analysis. We aimed to assess differences in the durations of PA with light, moderate to vigorous intensity, and sedentariness between the MW8 and the MM+. Therefore, only participants were included, for which data from both sensors were available. Second, we calculated the total durations of moderate to vigorous activity intensity for the three assessment methods, as the primary aim of this study was to compare the assessed PA levels and especially sedentariness. Traditionally, activities are considered to be moderate and vigorous activities when they were performed for a minimum of ten minutes without intermission. Thus, the present results regarding moderate to vigorous intensities are not comparable to previous results. Third, the self-estimated PA levels refer to the month prior to the sensor-measurements. We chose to use the GPAQ 50+ because its score refers to a usual week in terms of PA within the last four weeks, as the aim of this trial was to assess habitual PA levels in healthy older adults. Finally, the results regarding PA levels and sedentariness assessed with MW8 and the MM+ were based on proprietary algorithms, which may or may not fit well for all ages. Even though the activity classification for the MM+ was found to be valid when compared to observation in young and older adults [30], as well as patient populations [31], previous studies suggest that the differentiation between sitting and standing deserves improvement [32].

Taking into account that sedentariness is an independent risk factor for several health outcomes [1–6]; the results of this trial highlight the relevance of quantifying habitual PA levels in older adults. Sensor-based approaches can offer important insights into the PA levels and PA types (e.g., sitting, lying) of older adults and they can increase the knowledge about mobility-related PA and sedentariness patterns. Furthermore, information regarding mobility-related PA (e.g., number of steps, transitions) offers a broad basis of starting points for deriving personalized interventions to improve PA in older adults sustainably. The first findings indicate that PA monitor-based interventions are effective in increasing PA levels in older adults [33]. Future research is needed to evaluate how motion sensor data can be used as a basis for such interventions and as an individual feedback. Finally, the use of motion sensors to assess PA levels and develop and evaluate interventions aiming to increase PA and decrease sedentariness in older adults could be of great benefit for older adults and the health care system.

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Chapter 3

Quantifying circadian aspects

Quantifying Circadian Aspects of Mobility-Related Behavior in Older Adults by Body-Worn Sensors – An “Active Period Analysis”

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Abstract: Disruptions of circadian motor behavior cause a significant burden for older adults as well as their caregivers and often lead to institutionalization. This cross-sectional study investigates the association between mobility-related behavior and subjectively rated circadian chronotypes in healthy older adults. The physical activity of 81 community-dwelling older adults was measured over seven consecutive days and nights using lower-back-worn hybrid motion sensors (MM+) and wrist-worn actigraphs (MW8). A 30-min and 120-min active period for the highest number of steps (MM+) and activity counts (MW8) was derived for each day, respectively. Subjective chronotypes were classified by the Morningness-Eveningness Questionnaire into 40 (50%) morning types, 35 (43%) intermediate and six (7%) evening types. Analysis revealed significantly earlier starts for the 30-min active period (steps) in the morning types compared to the intermediate types ($p \leq 0.01$) and the evening types ($p \leq 0.01$). The 120-min active period (steps) showed significantly earlier starts in the morning types compared to the intermediate types ($p \leq 0.01$) and the evening types ($p = 0.02$). The starting times of active periods determined from wrist-activity counts (MW8) did not reveal differences between the three chronotypes ($p = 0.36$ for the 30-min and $p = 0.12$ for the 120-min active period). The timing of mobility-related activity, i.e., periods with the highest number of steps measured by hybrid motion sensors, is associated to subjectively rated chronotypes in healthy older adults. The analysis of individual active periods may provide an innovative approach for early detecting and individually tailoring the treatment of circadian disruptions in aging and geriatric healthcare.

Keywords: circadian motor behavior; body-worn sensors; older adults

1. Introduction

Morning lark or night owl—what is your preferred time of the day? The growing knowledge of and interest in the impact of circadian rhythms in daily life refers to circadian medicine [1], where individual chronotypes and circadian characteristics play a key role in society and health care [2].

Physiological processes and behaviors synchronized to a 24 h structure are defined as circadian (lat. circa = approximately, -dian = day) [3,4]. The stability of circadian behaviors is especially relevant in older adults and geriatric health care, where aspects of circadian behavior may show deviations ranging from age-associated changes in subjective chronotypes [5] to clinical syndromes [6]. Disease-related changes of the circadian system occur, for example, as sleep disturbances with reversed day-night rhythms [7], or sundowning phenomena with increased levels of physical activity (PA) and behavioral disturbances in the afternoon and evening hours [8,9]. Disturbed circadian rhythms cause a significant burden for both the patients themselves as well as their caregivers [10] and often lead to institutionalization, especially in home-dwelling dementia care [11].

Within chronobiological research and geriatric sleep medicine, subjective or proxy-based psychopathometric instruments [12,13] and objective approaches like polysomnography or body-worn motion sensors are usually applied to assess circadian characteristics [14]. Most commonly, uni- and multi-axial accelerometers attached to the non-dominant wrist, so called actigraphs [15], are used as ambulatory assessment to quantify circadian motor behavior. The accumulated raw activity counts of wrist movements are analyzed by non-parametric methods—e.g., by deriving an acrophase that refers to the timing of the peak activity within an day [16], or analyzing the intra-daily variability, and the inter-daily stability of the counts per minute [17]. As these actigraphs only record wrist movements, these measurements and analyses provide a general assumption of temporal aspects of PA and do not enable to detect specific motor behavior patterns. Studies in geriatric care and investigations in community-dwelling older adults indicate the wrist activity to be independent of the distribution of the step count [18,19]. Therefore, such actigraphic measurements do not allow to derive personalized interventions, e.g., like physical activity programs scheduled as circadian zeitgebers [20,21].

Hybrid motion sensors attached to the lower back can detect the patients' body postures over several days, allowing to analyze individual mobility patterns concerning mobility-related behavior [22]. First studies conducted with older adults have investigated inter-daily walking duration and step count with sensors attached to the participants' trunk or thigh [23,24]. Up to now, only a few approaches have been developed and applied to investigate the temporal distribution 65 of mobility-related PA in older adults. For example, the investigation led by Lim [18] analyzed the gait activity during the day using the number of active minutes (≥4 steps per minute), and the study reported by Paraschiv-Ionescu [25] analyzed the complexity of motor behavior by barcoding the participants' motor behavior during the day. Both studies used sensor-based approaches to monitor mobility-related physical activity but did not address chronotypes and circadian aspects of motor behavior. As these mobility-related measurements promise an added value over wrist-worn actigraphs for use in diagnostics and treatment, the primary aim of this study is to investigate the association between the timing of mobility-related active periods and subjectively rated chronotypes in healthy older adults.

2. Materials and Methods

2.1. Study Design

This investigation was part of the ChronoSense project—a cross-sectional study to investigate the use of body-worn motion sensors to quantify chronotypes in older adults (DRKS00015069, German clinical trial register). The study protocol was approved by the Ethics Committee of the Medical Association North Rhine (registration number 2018192) and the Ethics Committee of the German Sport University Cologne (registration number 156/2017).

2.2. Participants

Participants were recruited by sending out emails with information brochures to local senior citizens' networks and to employees of a large municipal association in the Rhineland region in Germany, and through word-of-mouth referrals. Furthermore, invitation letters were sent to persons who expressed interest in participating in studies of the Institute of Movement and Sport Gerontology in the past. These persons had not participated in any studies in the previous year.

Inclusion criteria for participation in the project were as follows: age of 65 years or older, community-dwelling, a score on the Mini-Mental Status Examination (MMSE) ≥24 [26,27], subjective health (self-reported), no full-time employment and written in- formed consent regarding the study procedures. Any acute or severe mobility impairment, cardiovascular disorder, cognitive disorder or neurological disease (assessed with the Functional Comorbidity Index (FCMI)) [28], which can interfere with functional mobility, led to exclusion from the project.

2.3. Instruments

The self-estimation of chronotype was assessed using the Morning-Eveningness Questionnaire (MEQ) [29]. The MEQ is a self-administered questionnaire, determining the circadian chronotype based on 19 questions concerning the participant's usual daytime preferences. Five chronotypes are distinguished based on the total score of the MEQ: definite evening type (16–30 points), moderate evening type (31–41 points), intermediate type (42–58 points), moderate morning type (59–69 points) and definite morning type (70–86 points). For further analysis, the moderate and definite evening type as well as the moderate and definite morning type were each grouped together. In order to determine the waking time during the day, the participants were asked to log their get up and got to bed times in a sleep diary [30].

The wrist-worn MotionWatch 8 (Camntech, Cambridge, UK) was used for the actigraphy-assessments. It integrates a triaxial accelerometer, a light sensor and an event marker button. The MotionWatch 8 (MW8) was attached to the wrist of the participants' non- dominant hand. The participants were asked to push the event marker button when getting up and going to bed. The sample frequency of the accelerometer was 50 Hz. The raw acceleration measurements were processed by the on-board software of the MW8 to produce a quantitative measure of the activity during each epoch. For this, the X, Y and Z-axes of the accelerometer were sampled with filtering at 3–11 Hz. The peak $X^2 + Y^2 + Z^2$ value was tracked. At the end of each second, the square root of the peak value from that second was calculated. This was compared to a threshold of 0.1 g. Values below this threshold were ignored to simplify the final activity graph. Activity that caused the acceleration signal to exceed the threshold was counted as activity. At the end of each epoch of 60 s, the number of activity counts were accumulated. This value was recorded as the 'Tri-Axial count' for the epoch.

The mobility-related measurements were conducted using the Dynaport Move Monitor + (MM+; McRoberts, The Hague, NL). The MM+ consists of a triaxial accelerometer, a triaxial gyroscope (sample frequency for both sensors: 100 Hz), a triaxial magnetometer, a barometer and a temperature sensor. Data can be collected for up to seven consecutive days. In order to enable a consistent recording of PA, waterproof self-adhesive foil (Opsite Flexifix, Smith and Nephew, London, UK) was used to attach the MM+ to the participants' lower back, approximately 3 cm right to the fifth vertebra of the lumbar spine (L5). The participants were asked not to remove either sensor during the measurement period. To ensure an assessment of habitual awake and rest phases, only sensor data of participants with four or more complete measurement days were included.

2.4. Data Collection

Data collection covered the period of one week. During an individual appointment in the laboratory, the MEQ was administered, and participants were equipped with the two sensors and received the sleep diary. Furthermore, the participants' living situation (e.g., marital status, income) as well as their health status (e.g., number and kind of chronic diseases) were assessed using a custom-made questionnaire.

At the end of the measurement period, the sensors were removed from the participants' body. The participants were asked to specify whether or not they had removed one or both sensors during the measurement and to indicate the period if this was the case. In order to ensure that the measurement period represented a habitual week in terms of the participant's PA and wake and rest periods, special events (e.g., acute illness) were noted.

2.5. Data Processing and Statistical Analysis

The MW8 raw data were processed using the validated proprietary MotionWare software (CamNtech, Fenstanton, UK). Total counts per 60 s epochs as well as the getting up and bedtimes based on the event markers set by the participants were included in the output. Average counts per minute were calculated for 24 h. The duration of wakefulness (time from getting up to bedtime) for each day was calculated. In case a participant forgot to set the marker, the corresponding time from the sleep diary was used instead.

The MM+ raw data were processed using the validated manufacturer's own algorithm (MoveMonitor, McRoberts, The Hague, NL). PA category (walking, stair walking, cycling, shuffling, standing, sitting and lying) as well as the categories not-worn, activity duration and number of steps per 60 s epoch were provided within the output. For the description of this study sample, the average durations of PA types and total number of steps were calculated for 24 h.

In order to quantify circadian aspects of mobility-related behavior, we determined an active period for each day. The active period was defined as the time interval in which the highest PA was measured during wakefulness (from getting up to bedtime). For the MW8, the active period was determined based on activity counts, and the active period of the MM+ was determined based on the number of steps. According to the recommendations of the American College of Sports Medicine to be active for a minimum of 30 min per day on five days per week [31], we chose to determine the active period for an interval of 30 min. Referring to the MEQ, rating the best time of the day for performing two hours of physically hard work, we chose to determine a 120 min active period [29]. Matlab R2020a (The Mathworks, Natick, MA, USA) was used to detect the time of the beginning of each active period. To this purpose, the total number of steps or counts over a time interval of 30 or 120 min was calculated repeatedly, starting with the first available data (when participants got up) and repeated by shifting the start of the time intervals to each next minute. This was repeated until the very last interval (30 or 120 min before the participant went to bed). Subsequently, all intervals were sorted in ascending order and the interval with the highest value (number of steps or number of counts) was determined as the active period. As the sensor measurements were started at 8 pm on day one and ended at 8 pm on day 8, the active periods were analyzed for day two (getting up) to day seven (going to bed). Finally, the mean start times of the 30-min and 120-min active phases were determined for each participant.

IBM SPSS Statistics 26.0 for Windows (International Business Machines, Armonk, NY, USA) was used for statistical analysis. Boxplots were used to identify extreme values. Values of more than three times the interquartile distance were excluded from further analysis. Subsequently, the Kolmogorov Smirnov test was used to examine data for normal distribution. One-way analyses of variance (ANOVAs) or Kruskal–Wallis tests were performed to assess differences in the start times of the active period between the three groups. Bonferroni post-hoc tests were used to examine significant differences. An alpha < 0.05 was considered to be statistically significant.

3. Results

3.1. Participants

A total of 118 persons were screened with regard to the inclusion criteria. Twenty-three persons declined to participate; 10 persons did not fit to the inclusion criteria. Eighty-five persons agreed to participate. Two participants became ill during the measurement period and were excluded from data analysis. One participant indicated that he was less active than usual during the measurement period, and one participant did not wear the sensors according to the instructions. The data of these two participants were excluded from analysis. Finally, the data of 81 participants were analyzed. Table 1 shows their characteristics.

Table 1. Sample characteristics

	N (%)	Mean	SD	Min	Max
Sample	81				
Female	40 (49.4)				
Age (years)		71.5	5.0	65	84
Mass (kg)		76.9	15.4	54	119
Height (cm)		170.3	8.3	154	188
MEQ score		57.7	9.9	31	77
Number of diseases		2.0	1.4	0	7
Duration of wakefulness (h)		15.9	0.8	13.5	18.1
Move monitor+	75				
Activity/posture [hh:mm]/24 h					
lying		09:01	01:38	06:18	14:29
sitting		09:13	01:53	05:08	14:13
standing		03:02	00:48	01:02	04:48
shuffling		00:29	00:10	00:11	01:11
walking		01:57	00:36	00:44	03:51
other activities *		00:05	00:11	00:00	00:59
not worn		00:13	00:25	00:00	03:07
steps/24 h		9860.1	3279.9	3278.0	17319.2
MotionWatch 8	66				
counts/min [24h]		317.9	87.3	121.6	556.9

MEQ—Morningness-Eveningness Questionnaire (assessment of subjective chronotypes; scores can range from 16–86. Scores of 41 and below indicate “evening types”. Scores of 59 and above indicate “morning types”. Scores between 42 and 58 indicate “intermediate types”); * summation of total activity durations for cycling and stair walking.

MM+ data were available for 75 (93%) participants. The MM+ data of six participants (7%) were missing due to technical problems. Six complete measurement days were available for 67 participants (83%). Seven participants (9%) completed five measurement days. One participant (1%) completed the minimum requirement of four measurement days. MW8 data were available for 66 (82%) participants. MW8 data of 15 (18%) participants were missing due to technical problems. Six complete measurement days were available for all 66 participants.

The distribution of self-estimated chronotypes and the corresponding characteristics of subgroups is shown in Table 2. Statistical analysis revealed no significant differences between groups in the sample characteristics and their general level of PA.

Table 2. Sample characteristics of self-estimated chronotype subgroups.

	Morning Type			Intermediate Type			Evening Type			
	N (%)	M	SD	N (%)	M	SD	N (%)	M	SD	p
Sample	40 (49.4)			35 (43.2)			2 (7.4)			
female	15 (37.5)			22 (62.9)			3 (50.0)			
Age [years]		72.1	5.2		71.4	5.1		67.8	3.1	0.10
Wakefulness [h/day]		16.1	0.6		15.8	0.8		15.9	0.8	0.55
MM+ Steps [number/24 h]	37	9791.2	3157.1	32	9823.9	3101.1	6	10478.4	4310.3	0.98
MW8 Counts/min [24 h]	30	316.8	73.9	30	319.1	103.2	6	317.9	40.0	0.98

MM+ Move Monitor+, MW8 MotionWatch 8.

3.2. Active Period Analysis

Figure 1 shows the comparison of the summed 30 min time intervals of the number of steps per minute for one subject from each chronotype group. The time of day at the peak of each curve indicates the beginning of the 30 min active period based on the step count for one participant of each chronotype group.

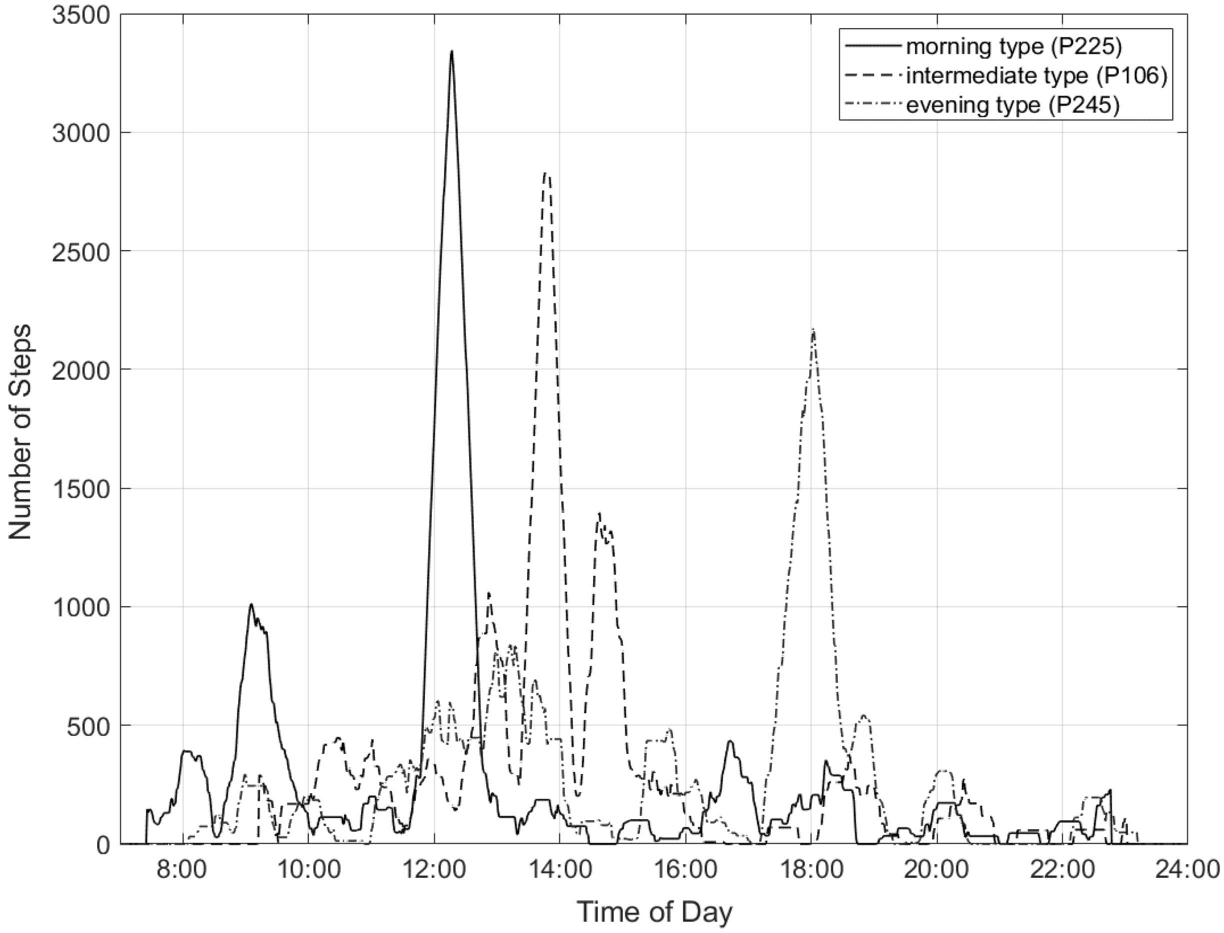

Figure 1. Exemplary analysis of 30-min active period.

Significant differences within the circadian aspects of the step count (MM+) between the three groups were detected (Figures 2 and 3).

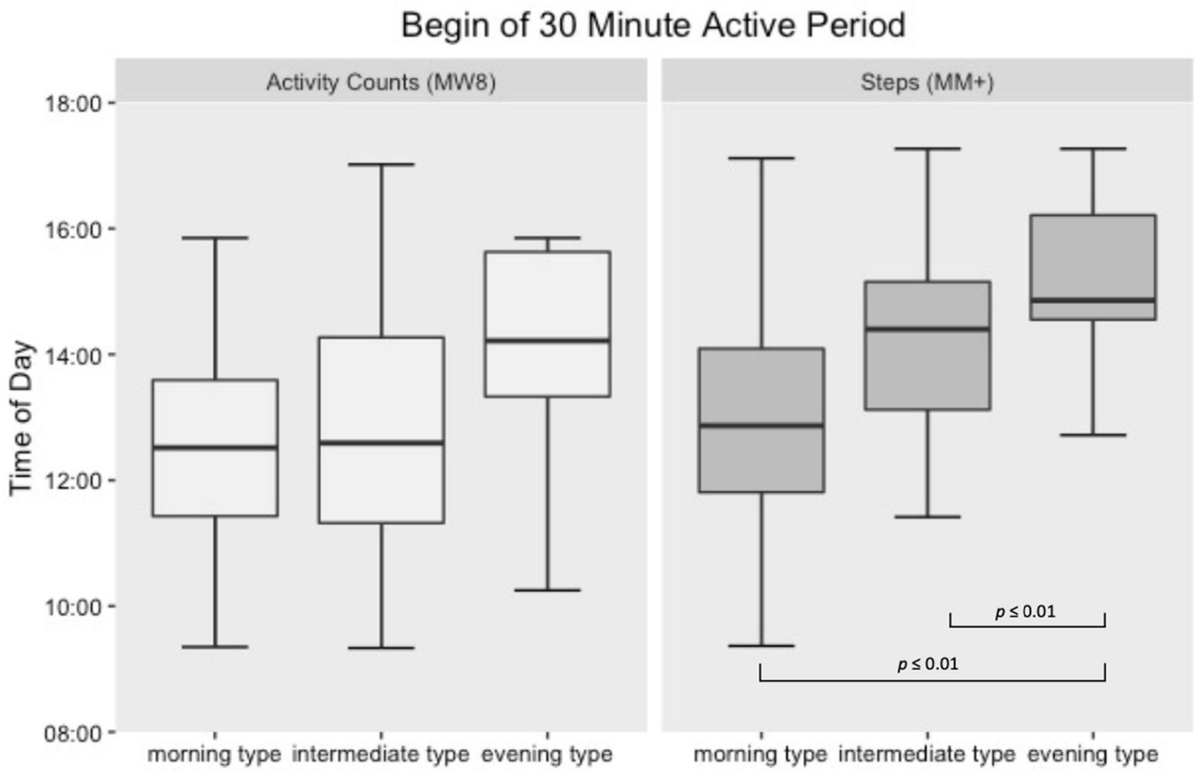

Figure 2. Box-plot illustration of 30-min active periods beginnings in relation to the subjectively rated chronotypes.

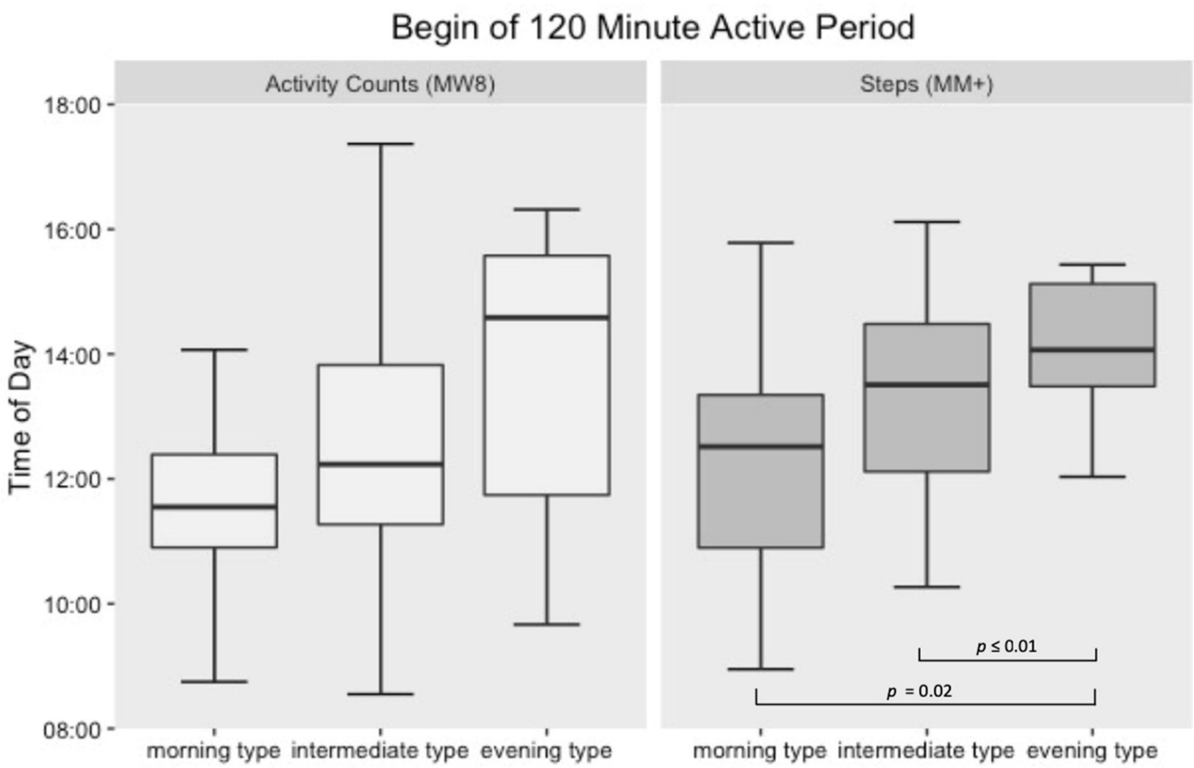

Figure 3. Box-plot illustration of 120-min active periods beginnings in relation to the subjectively rated chronotypes.

Compared to the morning type group, the intermediate type group showed a delay in their 30-min active period of approximately one hour ($p \leq 0.01$) and the evening type group a delay of approximately two hours ($p \leq 0.01$), respectively. These results were also found for the 120-min active period. Compared to the morning type group, the intermediate type group showed a delay of approximately one hour ($p \leq 0.01$) and the evening type group a delay of approximately two hours ($p = 0.02$), respectively. No differences within the circadian aspects of the activity counts (MW8) were detected regarding the three chronotype groups for both the 30- and 120-min active periods.

4. Discussion

The primary aim of this study was to investigate the association between the timing of mobility-related active periods and subjectively rated chronotypes in healthy older adults. The analysis revealed significant differences in the starting times for the 30-min and 120-min active period (steps) between the chronotypes. The starting times of the active periods regarding the wrist-activity counts did not reveal differences between the three chronotype groups.

The "active-period" analysis is a novel approach in this field of research. Whereas the usually applied wrist-worn actigraph approach showed no differences in activity-related behaviors over the three chronotype groups, this study's results reveal the hybrid motion sensor to be able to quantify circadian aspects of mobility-related behavior, i.e., regarding the number of steps. The timing of the peak wrist activity within a day, usually reported as acrophase for wrist-worn actigraphy [16], seems to be independent of the timing of the peak gait activity, reported as active period. These differences between objectively measured wrist-based activity (counts) and mobility-related behavior (steps, postures) are comparable to previous results [19]. Additionally, studies applied in an acute geriatric care setting reported three peaks in the wrist-measured physical activity at 9 am, 12 pm and 5 pm, referring to the patients' meal times and showing no relation to the distribution of the step count within the patients' day [18]. As compared to the usually used wrist-worn actigraphy approach in chronobiological research and geriatric sleep medicine, analyzing the active period of mobility-related behavior seems to provide more clinically relevant and essential information. Such circadian aspects of mobility-related behavior could be applied to assess circadian disruptions based on the temporal distribution of the step count within a day and subsequently derive, individually tailor and evaluate interventions to treat circadian disruptions, e.g., exercise approaches based on step counts [20,21,32].

The participants included in this study were healthy, community-dwelling older adults, on average 72 years old (SD 5), with a daily step count ranging from 3278 to 17,320 with on average 9860 steps per day (SD 3280). These activity measures reveal a general active lifestyle, as the endorsed level of 7000–10,000 steps per day was almost achieved in this

group [33]. With a mean of 317 activity counts per minute [24 h] (SD 87), the study sample shows comparable levels to other studies using the same actigraphy approach [34].
The included participants subjectively rated themselves mainly as morning type (*n* = 40, 49.4%) and intermediate type (*n* = 35, 43.2%), but only six participants rated themselves as evening type (7.4%). This distribution of chronotypes is comparable to previous studies, which reported more morning types in association with higher age [5].
An analysis and interpretation of this study and its results should consider the following methodological limitations: established by Horne and Ostberg [29], the Morningness-Eveningness Questionnaire usually categorizes five chronotypes. The definite and moderate morning- and evening types were accumulated in order to analyze differences between the three main chronotypes. The current analysis did not reflect inter-daily consistency of active periods. Future analysis should address these aspects, e.g., via coefficient of variance. A potential selection bias should be taken into account, as the sample has been shown to be highly active with approximately 10,000 steps per 24 h.
The results of this study contribute to the growing knowledge and interest on the impact of circadian rhythms in daily life and healthcare [1,2]. Analyzing the starting times of the active periods for mobility-related behavior, e.g., by the number of steps measured by hybrid motion sensors (MM+), seems to be a clinically relevant approach to quantify circadian aspects in healthy older adults. Analyzing circadian aspects of mobility- related activity, and potentially also temporal patterns of inactivity, could play a key role in aging research and geriatric healthcare, especially in the assessment and treatment of circadian disruptions. In addition to the presented results of not showing differences in the assessment of active periods, the wrist-worn actigraphy approach (here MW8) does not allow to derive, apply and evaluate individually tailored interventions. This is essential for its clinical application, and therefore limits its use in general and especially in geriatric healthcare [19]. The presented "active period analysis" provides an innovative and clinically relevant approach to quantify circadian aspects of mobility-related behavior with body-worn sensors in older adults. Especially in patients suffering from circadian disruptions, an individual (in)active period could be used to derive, apply and evaluate step-based interventions [35] potentially combined with day-structuring approaches. The individual active period analysis may improve the early detection and individual tailoring in the treatment of circadian disruptions in aging and geriatric healthcare that may have promising effects for patients, caregivers and geriatric healthcare [1,2].

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and has been approved by the Ethics Committee of the German Sport University Cologne (registration number 156/2017) and the Ethics Committee of the Medical Chamber Northrhine (registration number 2018192).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author, upon reasonable request. The data are not publicly available due to privacy/ethical restrictions.

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Conflicts of Interest: The authors declare no conflict of interest.

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Chapter 4

The role of circadian aspects in acute dementia care

Circadian Aspects of Mobility-Related Behavior in Patients with Dementia: An Exploratory Analysis in Acute Geriatric Psychiatry

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Background: Analyzing patients' mobility-related behavior may improve the assessment of motor behavior in dementia, however, few studies addressed circadian aspects of mobility. This cross-sectional explorative study analyzed the timing of peak mobility-related behavior, the prevalence of mobility-related sundowning and nocturnal mobility-related behavior and associated clinical characteristics in acute geriatric psychiatry.
Methods: Mobility-related behavior of 73 patients (M: 81 years) was measured over 48 h using lower-back worn hybrid motion sensors. We derived the start of the 30- min period with peak gait activity (highest number of steps) for each day and the number of nocturnal steps taken from 10PM to 7AM. Professional caregiver ratings of the patients' motor behavior were conducted within the Neuropsychiatric Inventory (NPI).
Results: The mean start time of peak gait activity was 2:37PM, but large variations in timing were found (range: 3:25AM–9:30PM). Twenty-five patients (34%) were identified as “sundowners”. Nocturnal mobility-related behavior was measured in 35 patients (53%), whereas professional caregivers assessed night-time disorders in only 19 patients (26%). Clinical characteristics of “sundowners” were not significantly different from other patients, except for lower doses of antipsychotics as compared to non-sundowners (M:1.6 mg/day; p = 0.015). The number of nocturnal steps was significantly associated to corresponding NPI ratings (Spearman's rho = 0.4; $p < 0.001$).
Conclusion: Analyzing the timing of peak gait activity and nocturnal step-count seem to provide clinical applicable information on the circadian aspects of mobility-related behavior in acute geriatric psychiatry. Even though the clinical validity needs to be evaluated, objective information on the individual circadian aspects of mobility-related behavior could help to personalize treatment with benefits for patients and caregivers.

Background

In 2019, more than 57 million people were living with dementia worldwide. It is expected that this number will rise to nearly 153 million in 2050.[1] Along the decline of cognitive functioning, the disease is characterized by the occurrence of neuropsychiatric symptoms (NPS). Within the course of the disease, almost every patient suffers from NPS.[2] NPS include psychopathological symptoms, such as delusions, hallucinations, depression, anxiety, and sleeplessness as well as additional behavioral symptoms such as agitation, apathy or sleep and night-time disorders.[3] Excessive motor behavior, clinically manifesting as for example, wandering or restlessness, is a core aspect of agitation in dementia. It often shows circadian aspects (lat. circa = approximately, -dian = day) such as increasing psychomotor disturbances in the second half of the day,[4–8] clinically known as *sundowning phenomenon*. Even though, sundowning behavior is known as a valid clinical condition, the phenomenon lacks consistent criteria for diagnosis and definition.[9] The temporal aspects of sundowning behaviors are often attributed to the evening hours,[6] however, it seems that the occurrence of the behavioral signs is not limited to the evening hours, but can occur in the afternoon[5,10] and continue into the night (e.g., nocturnal wandering or sleep-wake reversals).[8,9]
The causal mechanisms and associated characteristics of sundowning behavior are still under-researched.[6] Previous results suggested that affected patients experience restlessness and sleep disturbances more frequently, receive more sedative medication and experience higher cognitive decline.[4] Sundowning behavior affects the patients themselves, as well as their families and caregivers, and often lead to hospitalization or institutionalization of community- dwelling patients.[6,11–13] The admission to a hospital is likely to initially exacerbate the symptomatology due to the change in environment and primary caregiver(s) and due to low staff-to-patient ratios.[14,15]
An accurate assessment of symptoms like nocturnal wandering or the sundowning phenomenon is key to initiate and tailor required treatment.[16,17] Wrist-worn actigraphy, measuring the presence or absence of arm movements and their intensity in activity counts per epoch (e.g., 60 s), is a well-accepted approach to ambulatory assess sleep and circadian rhythms and has extensively been used in patients with dementia.[4,7,18,19] Within this context actigraphs are used to assess the person's physical activity levels continuously over long periods of time, however, they do not enable to assess specific aspects of motor behavior such as the type of activity (e.g., walking), gait parameters or body-postures (e.g., lying, sitting, upright).[20] The assessment of body-postures is essential to differentiate sedentary behavior from other motor behaviors such as mobility-related behavior.[21] Furthermore, previous studies in geriatric care and in community-dwelling older adults indicate that the wrist activity is independent of the distribution of the step count.[22–24]
Recently, hybrid motion sensors (e.g. including three-dimensional accelerometer, magneto-

meter, and gyroscope) attached to the lower back have been used to assess mobility-related behavior in patients with dementia.[25] Together with corresponding algorithms this instrumental setup allows to quantify body postures (e.g., time spent sitting), postural transitions (e.g., number of sit-to-stand transitions), and activity types (e.g., number of steps) continuously over 24 h/ day.[20,26]

Assessing patients' motor behavior with regard to mobility- related and sedentary behavior could enable to quantify specific circadian patterns of motor behavior such as nocturnal wandering. Such analytic approaches may be used to improve the diagnosis of NPS as well as the planning and evaluation of (non-) pharmacological treatments, as they provide relevant outcome measures[27] that can be easily monitored and understood (e.g., number of steps) by a multi- professional treatment team, patients and caregivers across health sectors.

First approaches aimed to investigate the temporal distribution of mobility-related behavior in older adults by analyzing parameters such as the number of steps in relation to the time of day[22,28,29] and during the night.[28] Monitoring mobility-related and sedentary behavior over long time-periods promises a valuable progress in the assessment of circadian rhythm-related disorders, such as sundowning behavior and nocturnal wandering.[25,30] Up to now, very few studies used data on mobility-related behavior to address circadian motor behavior in dementia.[28]

Therefore, the primary objective of this exploratory study is to investigate the circadian aspects of mobility-related behavior in patients with dementia in acute hospital care by pursuing the following research questions: (a) What is the timing of peak gait activity during the day? (b) What percentage of patients show peak gait activity in the afternoon and evening hours (sundowning) and do their clinical characteristics differ from other patients? (c) What percentage of patients show nocturnal mobility-related behavior and how is it associated to clinical characteristics?

Methods

Study design

This descriptive, cross-sectional study uses baseline data from the ExCaDem trial—a randomized controlled trial (RCT) to investigate the effects of a short-term exercise program on neuropsychiatric signs and symptoms in acute dementia care (DRKS00006740, German clinical trial register). The study protocol was approved by the Ethics Committee of the German Sport University Cologne and the Ethics Committee of the Medical Chamber Northrhine (reference number: 2014216).

Participants

Patients were recruited from three specialized dementia care units of a geriatric hospital. All patients were assessed for eligibility by two senior geriatric psychiatrists. The following inclusion criteria were applied: diagnosis of dementia according to ICD-10; clinical exclusion of delirium based on the validated German version of the Confusion Assessment Method[31,32]; ability to perform the Timed Up and Go Test (TUG) without human assistance[33]; one week minimum of stay before enrollment into the study in order to help patients become familiarized with the ward setting. The latter inclusion criterion was removed in the course of the study due to high dropout rates in the RCT caused by early discharges. In order to reduce the high dropout rates in the RCT mainly caused by early discharges, the latter inclusion criterion was removed in the course of the study. The adjustment of this inclusion criterion was considered within the statistical analyses and the interpretation of its results.

Written informed consent from the patient or the patient's legal guardian was required. With a score on the Mini-Mental Status Examination (MMSE)[34] >20, the patient was introduced to the project and asked if he or she wanted to participate. If the patient was able to explain the content and aims of the project in his/her own words, the patient was considered to be able to give the informed consent on his/her own. With a score <20 on MMSE, the patient's legal guardian was asked whether a project participation would be in the interest of the potential participant. However, if the patient in this case expressed that he/she did not want to participate in the project, the patient's decision was respected. For each consent procedure, the respondents received appropriately adapted information about the project and adapted consent forms. The applied consent process has been confirmed by the responsible ethics committee and follows recommendations of the task force on ethical and legal questions of the Association of Neuropsychopharmacology and Pharmacopsychiatry.[35]

Instruments

As part of the hospital's standardized comprehensive geriatric assessment within the first week after admission, trained medical specialists assessed the patients' cognitive functioning and mobility using the MMSE and the TUG, respectively.

The patients' NPS and perceived caregiver burden were rated using the neuropsychiatric inventory (NPI) over 1 week retrospectively.[36] The NPI was conducted in a proxy-based interview covering 12 psychopathological domains: delusions, hallucinations, agitation/ aggression, depression/dysphoria, anxiety, elation/euphoria, apathy/ indifference, disinhibition, irritability/lability, aberrant motor behavior, sleep and night-time behavior disorders, appetite/eating changes. Each domain was rated regarding the frequency of symptoms with a 4-point scale (1 indicating rare and 4 very frequent) and the severity of symptoms with a 3-point scale (1 indicating minor and 3 significant). The score of the individual domains were obtained by multiplying the domain's frequency and severity scores. Domains with no corresponding symptoms were rated 0. The total score of the NPI was calculated by summing the 12 domain scores, resulting in possible scorings from 0 to 144 points (0 points = NPS not present).[34] The perceived caregiver burden was ranked for each of the 12 domains based on a 5-point scale: 0 points indicating no caregiver burden and 5 points indicating maximum caregiver burden. The NPI caregiver burden total score ranges from 0 to 60 points, with 0 indicating no perceived caregiver burden.

The patients' circadian mobility-related behavior was assessed with the uSense sensor, a non-commercial activity monitor developed in a large EU project (FARSEEING, FP7/2007–2013, grant agreement n. 288940), suitable for ambulatory, uninterrupted long-term motion measurement.[37] The uSense sensor is a 3D hybrid motion sensor incorporating a tri-axial accelerometer, gyroscope, and magnetometer. Its psychometrical quality has been reported, confirming the construct validity, test-rest reliability, and feasibility in older adults with cognitive and motor impairment.[37] Data were sampled at 100 Hz and stored on an internal storage medium. The sensor devices were attached to the patients' lower back, approximately 3 cm right to the fifth vertebra of the lumbar spine (L5) using waterproof self-adhesive fixing foil (Opsite Flexifix, Smith and Nephew, London, UK), enabling a consistent recording of mobility-related behavior. Each patient was advised to wear the sensor for 72 consecutive hours. In order to control the influence of therapy sessions on the patients' mobility-related behavior, we aimed to conduct the uSense measurements primarily on weekends (Friday noon – Monday noon), on which no exercise- or occupational therapy sessions were offered at the time of the trial. If a patient experienced the sensor-attachment as uncomfortable or painful, the nursing staff motivated the patient once to continue the measurement. If the patient repeated his unwillingness to tolerate the sensor device, the nursing staff removed it. In order to check upon consistency between the motion sensor recordings and the nursing staffs' observations, routine clinical protocols for the patients' measurement periods were extracted from the hospital information system.

Data processing and analysis

Based on the sensor data, patients' postural events and activity levels were identified by means of a hierarchical classification approach using established algorithms. Metabolic equivalent of tasks (METs) was calculated based on activity counts.[38] Intervals in which METs are below or equal to 1.5 were identified as “sedentary” while intervals above 1.5 METs are identified as “active”.[39] An angle between the vertical axis and the medio-lateral or the anterior-posterior direction of the trunk below 30° was used to identify intervals of “lying” within “sedentary” periods. Within “active” periods, steps and gait were detected using acceleration and an adaptive algorithm for calculation.[40]

Processed sensor-data of the first 48 h beginning at the start of the sensor measurements were included for further analysis. Data of patients who did not complete 48 h of sensor-measurements were excluded from further analysis. The amount of physical activity and the number of steps were quantified as means, standard deviations, minima and maxima within the descriptive statistics.

Circadian aspects

In order to assess circadian aspects of mobility-related behavior, the total number of steps in time intervals of 30 min were calculated repeatedly, starting with the first available data point (start time of measurement on day one) and by shifting the start of the time intervals to each next minute. This was repeated until the very last interval (30 min before the end of measurements on day two). Subsequently, an active period – defined as the 30 min time interval with the highest number of steps — was determined for each day of measurement.[29] The starting time of the mean active period, as well as the absolute difference of active period starting times between the first and the second measurement day were calculated for each patient. Within this explorative analysis, the absolute difference of active periods was used as an indicator for the consistency of the active period starting times, with lower values indicating a similar timing of active periods on both measurement days. In order to assess the prevalence of sundowning, the patient's peak active period starting times per day were assigned in line with the nursing staffs' working shifts[3] as follows: Patients with active period starting times between 7 AM and 1:59 PM on both days were designated as *morningers*. Patients with active period starting times between 2 PM and 9:59 PM on both measurement days were designated as *sundowners*. Patients for whom both active periods did not start within the same interval (e.g., 7 AM–1:59 PM or 2 PM–9:59 PM) were defined as *mixed types*.

The nocturnal mobility-related behavior was assessed based on the number of steps taken between 10 PM and 6:59 AM (time period of the night shift). Number of steps were only assessed in periods, in which physical activity was classified as active sitting/standing or walking for more than 15 min. This approach was taken in order to exclude mobility-related activity that occurred during care-planned interventions (e.g., regular toilet trips during the night). The number of steps was summed for each night. Patients with nocturnal mobility-related behavior in none, one and both nights were identified. Matlab_R2021a (The Mathworks, Natick, US) was used for analyses of active periods and nocturnal mobility-related behavior.

Descriptive Measures

Information on age, gender, Body-Mass-Index (BMI), ICD-10 diagnosis, MMSE score, time to perform the TUG were obtained from the hospital information system and reported as measures of central tendency (means or median, standard deviation or interquartile range, minima, maxima) within the descriptive statistics. Furthermore, the patients' doses of sedative medication for the 48-hour period of the activity assessment were obtained from the hospital information system. Antipsychotic doses were converted into olanzapine-equivalents (OED) in mg/24h[41] and doses of benzodiazepines into diazepam-equivalents (DED) as mg/day.[42]

Statistical Analyses

Statistical analyses were conducted in RStudio 1.4.1106 for macOS (RStudio, Boston, US).[43]

Examination of normal distribution (Shapiro-Wilk test) and identification of extreme values (boxplots) revealed a skewed distribution of most continuous variables. Log-transformation of the data did not achieve normal distribution; hence, statistical analyses were performed using non-parametric tests.

Characteristics of the three active period groups (morningers, mixed types, and sundowners) were compared with Fisher's Exact Test for categorial variables (dementia diagnosis, gender, weekday of measurement) and a Kruskal-Wallis-test for the variable age.

To investigate how sundowners differ from the other subgroups regarding their mobility-related behavior, cognitive performance, sedative medication and NPS (i.e., restlessness, apathy, sleep & nighttime behavior) a multivariate Kruskal-Wallis-Test (non-parametric equivalent of a multivariate analysis of variance) was performed using R package ULT.[44] The mean starting time of the active period, mean number of steps within the active period, number of steps per night, dose of sedative medication (DED, OED), NPI subscores for apathy, aberrant motor behavior, sleep & night-time behavior disorders and care giver burden caused by these disorders were included in the multivariate analysis as dependent variables. A significant difference was analyzed with Kruskal-Wallis-Test for each dependent variable. Post-hoc analyses using pairwise Dunn tests with Bonferroni adjustments were conducted for variables with a significant Kruskal-Wallis-Test to assess differences between groups.

Associations between nocturnal mobility-related behavior (mean number of nocturnal steps, number of nights with mobility-related behavior) and clinical characteristics (MMSE, TUG, the mean starting time of the active period, mean number of steps within the active period, DED doses, OED doses, NPI subscores for apathy, aberrant motor behavior, sleep & night-time disorders and care giver burden caused by sleep & nighttime disorders) were analyzed with Spearman's rank correlation coefficients (r_s). Cohen's (1988) guidelines for interpreting the magnitude of a correlation were applied.[45] A correlation coefficient of $r_s \geq 0.1$ was considered small, $r_s \geq 0.3$ medium and $r_s \geq 0.5$ large in magnitude. For all tests, an alpha <0.05 was considered statistically significant.

Results

Participants

Overall, 226 patients were screened for eligibility over the period of one year. Eighty-seven patients met the inclusion criteria and their legal guardian's consent for participation was obtained. One participant withdrew the consent for participation before the initiation of sensor-measurement. The sensor-measurements were started with 86 participants. Data collection period covered less 48 h in nine participants (10%) due to premature sensor removal and four participants (5%) due to recording problems. Finally, data of 73 patients (44% female, *n* = 32) were included in the analysis. The sample characteristics, NPI scores and doses of sedative medication as well as the patients' average physical activity levels are presented in Table 1. The mean period from admission to the measurement of mobility-related behavior (measurement day) was 8.8 days (SD: 9.7 days). The analysis of the measurement day's influence on the mobility-related behavior and proxy-rated NPS revealed small, non-significant correlations: Spearman's rho (r_s) was −0.02 for the number of steps per day (p = 0.878), r_s was −0.11 for the total NPI-score (p = 0.368), r_s was −0.02 for the NPI subscore on aberrant motor behavior (p = 0.902), r_s = 0.07 for the NPI subscore apathy (p = 0.569), r_s = −0.12 for the NPI subscore sleep and nighttime behavior disorders (p = 0.321) and r_s = −0.06 for the NPI subscore care giver burden caused by sleep and nighttime disorders (p = 0.594).

Table 1: Sample characteristics (N = 73, 32 female).

	N (%)	M	SD	Min	Max
Age [years]		81	6	67	95
Diagnosis					
Dementia in Alzheimer's disease	26 (36)				
Vascular dementia	12 (16)				
Lewy-body-dementia	1 (1)				
mixed Type of dementia	34 (47)				
MMSE	73	18.2	5.0	7.0	27.0
Neuropsychiatric inventory	73	21[a]	19[b]	0	48
Caregiver burden (NPI)	28 (38)	9[a]	10[b]	0	26
Benzodiazepine dose (DED) [mg/day]	20 (27)	3.4	2.1	0.1	12.5
Antipsychotic dose (OED) [mg/day]	63 (86)	2.5	2.4	0.2	12.7
TUG [sec]	73	14.4	6	7.3	33.6
Posture/activity type [hh:mm]/24h	73				
lying		11:16	2:16	3:25	16:33
sitting/standing inactive		10:05	2:13	3:45	15:31
sitting/standing active		1:03	0:29	0:16	3:12
walking		1:27	1:05	0:09	7:03
no status		0:09	0:13	0:00	1:02
Steps/24h	73	7704	6098	608	44774

Note: Neuropsychiatric Inventory score 0–144, 0 = not present; NPI caregiver burden score: 0–60, 0 = not present.
Abbreviations: DED, Diazepam equivalent dose; M, mean; Max, maximum; Min, minimum; MMSE, Mini Mental Status Examination; NPI, Neuropsychiatric Inventory; OED, Olanzapine equivalent dose; SD, standard deviation; TUG, Timed Up and Go Test.
[a] Median.
[b] Interquartile range

Exemplary analyses of mobility-related behavior

The analysis revealed a high variability in the daily active period starting times and nocturnal mobility-related behavior between and within the patients. Figure 1 illustrates the number of steps measured continuously over 48 h in 30-minute intervals and the corresponding nursing records of four patients, whose curves represent the variety of the results. The nursing staff's observations regarding the general estimation of mobility-related behavior within the morning (6:30 AM–2:30 PM), evening (1:30 PM–10 PM) and night shift (9:30 PM–7 AM) primarily matched with the sensor-based measurements. In individual cases, the nursing staff's observations differed from the sensor-based measurements, for example, Figure 1, panel C.

Circadian aspects of mobility- related behavior

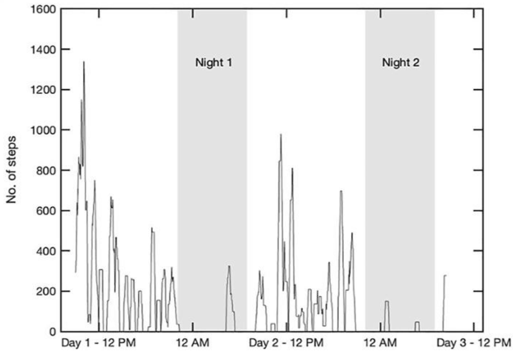
The mean 30-minute active period started at 2:37 PM (SD = 3 h 16 min, range = 3:25 AM–9:30 PM). Within this half an hour the patients walked 957 steps (SD = 461 steps, range = 111–2989 steps) on average. The analysis identified 25 patients (34%) as sundowners (active periods on both days starting between 2 PM and 9:59 PM) and 14 patients (19%) as morningers (active periods on both days starting between 7 AM and 1:59 PM)—see Table 2. Thirty-four patients (47%) started their active periods during the night (10 PM– 06:59 AM) or in the morning on one day and in the afternoon or the night on the other day. They were identified as mixed type. For none of the patients both active periods started during the night. Table 2 shows the characteristics of the three subgroups and results of the statistical comparison. The analysis revealed no significant differences between the three subgroups in the distribution of gender, age, dementia diagnosis and weekday of measurement.

Table 2: Characteristics of sundowners (active period on both days between 2 PM and 9:59 PM; *n* = 25); mixed types (active period on only 1 day between 2 PM and 9:59 PM or between 7 AM and 1:59 PM; *n* = 34) and morningers (active period on both days between 7 AM and 1:59 PM; *n* = 14).

	Morningers		Mixed type		Sundowners		
	n	**Median (IQR)**	**n**	**Median (IQR)**	**n**	**Median (IQR)**	***p***
Gender							
Female	8		13		14		0.500
Male	6		21		11		
Age [years]	14	80.0 (3.8)	34	79.0 (9.5)	25	82.0 (7.0)	0.552
Diagnosis							0.654
Alzheimer's dementia	6		12		12		
Vascular dementia	1		4		3		
Lewy-body-dementia	1		0		0		
Mixed type	7		17		10		
Weekday of measurement							0.567
Weekdays	4		6		7		
Weekends	10		28		18		

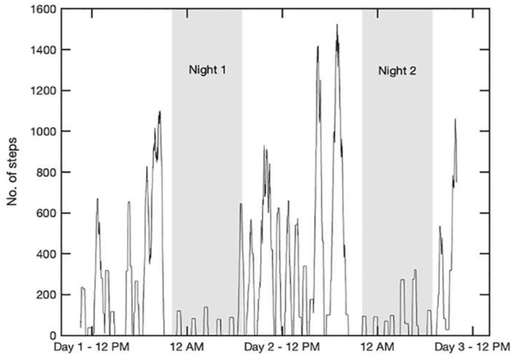
Note: Results of the Fisher's Exact Tests for categorial variables (gender, dementia diagnosis and weekday of measurement) and the Kruskal-Wallis-Test for the variable age. For all tests, an alpha <0.05 was considered statistically significant.
Abbreviation: IQR, Interquartile range.

A Morninger, few matches with clinical records.
80 years (m); VD; MMSE: 23; NPI-M: 8; NPI-S: 6; start of mean active period: 10:42 AM; steps/24h: 6562



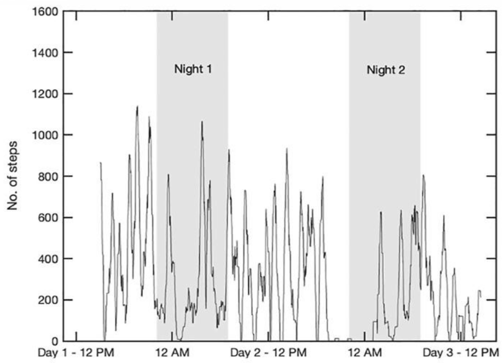
Day 1: *“Patient is mobile on the ward.”* **Night 1:** *“Patient slept through the night. One bathroom visit.”* **Day 2:** *“Patient appeared calm. Attended programs on the ward.”* **Night 2:** *“Patient slept through the night. One bathroom visit.”*

B Sundowner, high agreement with clinical records.
82 years (f); VD; MMSE: 12; NPI-M: 0; NPI-S: 0; start of mean active period: 7:46 PM; steps/24h: 10895



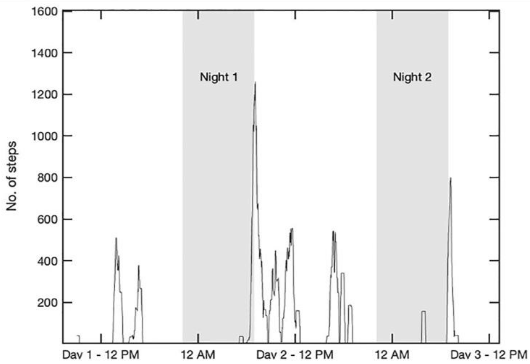
Day 1: *“The patient walks confused across the ward, appears calm and friendly.”* **Night 1:** *“The patient slept at regular checkups.”* **Day 2:** *“The patient walked disorientated across the ward. In behavior calm and friendly in contact.”* **Night 2:** *“The patient slept at regular checkups, excluding bathroom visits.”*

C Pronounced nocturnal mobility-related behavior, few matches with the clinical records.
84 years (f); VD; MMSE:16; NPI-M: 0; NPI-S: 8; start of mean active period: 7:14 PM; steps/24h: 13925



Day 1: *“The patient is mobile on the ward. Appeared restless at times.”* **Night 1:** *“Patient slept through the night. Regular checks.”* **Day 2:** *“The patient appeared confused. Walked into different patient rooms, […]. Calmer in the evening.”* **Night 2:** *“The patient slept until ca. 1 AM. Afterwards the patient walked confused across the ward.”*

D Long periods without mobility-related behavior in the afternoon; few matches with clinical records
89 years (m); AD; MMSE: 8; NPI-M: 4; NPI-S: 0; start of mean active period: 9:20 AM; steps/24h: 4027



Day 1: *“Patient attended meals and then went to bed after lunch. The patient appeared restless in the evening. Walks confused around the ward.”* **Night 1:** *“Patient slept through the night.”* **Day 2:** *“Patient walked disorientated across the ward during the morning and appears restless. In the evening.”* **Night 2:** *“Patient slept through the night. One bathroom-visit.”*

Figure 1: Plots of four patients' mobility-related behavior (number of steps) measured by a hybrid motion sensor over 48 h in 30-minute intervals. The graphs show the beginning of each 30-minute interval throughout the measurement period and the corresponding step count within the interval. The highest peak of each day indicates the 30-minute active period. AD, Alzheimer's disease; (f), female; (m), male; MMSE, Minimental Status Examination (score 0–30, higher scores indicating better functioning).

The multivariate Kruskal-Wallis-Test showed a statistically significant difference between the active period subgroups in the circadian apsects of mobility-related behavior and sedative medication (Chi square = 79.3, df = 24, $p < 0.001$). Individual Kruskal- Wallis-Tests attributed the significant differences to the mean active period starting times ($p < 0.001$) and the doses of antipsychotic medication ($p = 0.015$). The pairwise post-hoc Dunn test with Bonferroni adjustments revealed significant differences between all groups in the mean active period starting times: The morningers' mean active period started significantly earlier as compared to the mixed type ($p < 0.001$) and the sundowners ($p < 0.001$). The sundowners' mean active period started significantly later as compared to the mixed type's mean active period ($p < 0.001$). Significant differences were also found between morningers and sundowners in the mean dose of antipsychotic medication between ($p = 0.012$). The results of the group comparisons are presented in Table 3.

Table 1: Comparison of sundowners (active period on both days between 2 PM and 9:59 PM; *n* = 25); mixed types (active period on only 1 day between 2 PM and 9:59 PM or between 7 AM and 1:59 PM; *n* = 34) and morningers (active period on both days between 7 AM and 1:59 PM; *n* = 14) regarding their mobility-related behavior, cognitive performance, sedative medication and neuropsychiatric symptoms.

	Morningers	**Mixed type**	**Sundowners**	
	Median (IQR)	**Median (IQR)**	**Median (IQR)**	***p***
Mean active period start time [hh:mm]	11:12[a,b] (1:47)	14:19[b,c] (2:22)	17:22[a,c] (2:35)	*<0.001*
Number of steps in active period	805 (531)	889 (512)	933 (566)	0.634
Nocturnal steps	0 (82)	77 (383)	10 (356)	0.288
TUG [sec]	12.1 (2.6)	12.8 (5.1)	14.6 (7.1)	0.273
MMSE	19.0 (7.8)	20 (6.8)	18 (4.0)	0.517
Benzodiazepines (DED) [mg/day]	0 (0)	0 (0)	0 (2.5)	0.438
Antipsychotics (OED) [mg/day]	3.0[b] (4.1)	1.4 (2.1)	0.8[c] (2.4)	*0.015*
Neuropsychiatric inventory				
Apathy/Indifference	0 (4)	0 (3.8)	0 (3)	0.810
Aberrant motor behavior	0 (4)	3 (4)	4 (4)	0.869
Sleep & night-time behavior disorders	0 (4.5)	0 (0)	0 (3)	0.812
Caregiver burden caused by sleep & night-time disorders	0 (1.5)	0 (0)	0 (1)	0.730

Note: Results of the multivariate Kruskal-Wallis-Test. Individual Kruskal-Wallis-Tests for each dependent variable were performed to investigate the significant difference indicated by the multivariate analysis. Significant differences are presented in italic. Post-hoc analyses were performed using pairwise Dunn tests with Bonferroni adjustments. For all tests, an alpha <0.05 was considered statistically significant.
Abbreviations: DED, Diazepam equivalent dose; IQR, Interquartile range; MMSE, Mini-Mental-Status Examination; OED, Olanzapine equivalent dose; TUG, Timed Up and Go Test.
[a]Significant different to mixed type.
[b]Significant different to sundowners.
[c]Significant different to morningers.

Figure 2 shows the mean active period starting time of all patients and the absolute difference of active periods in hours between measurement day one and two. The mean absolute difference between active period starting times of day one and two was 3 h 59 min (SD: 2 h 42 min; range: 1 min - 11 h 46 min).

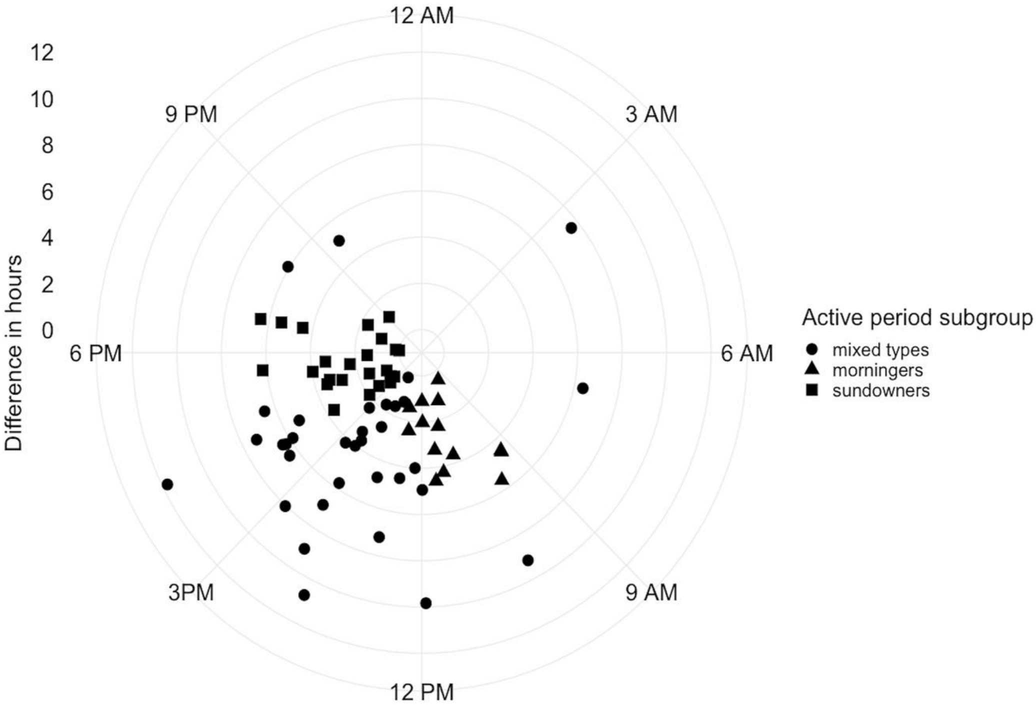


Figure 2: Circular plot of the mean 30- minute active period starting time on day one and two (circumference) and absolute difference of active periods starting times between measurement day one and two (radius).

The analysis of nocturnal mobility-related behavior revealed breaks from lying for more than 15 min in at least one of the two measurement nights (10 PM to 6:59 AM) for 39 patients (53%). Thirty-four patients (47%) did not show mobility-related behavior in either of the measurement nights. Twenty-five patients (34%) showed nocturnal mobility-related behavior in one night and 14 patients (19%) in both nights. The mean number of steps during the night for patients with nocturnal mobility-related behavior was 329 (SD 295). The proxy-based rating of sleep & night-time behavior disorders revealed symptoms (NPI subscore >0) in 19 patients (26%) with a median score of 6/12 points (range = 3–9). Table 4 illustrates the associations between nocturnal mobility behavior (number of nocturnal steps and number of nights with nocturnal mobility-related behavior) and clinical characteristics. The number of nocturnal steps was significantly correlated to the NPI subscore for sleep & nighttime disorders (r_s = 0.39; p < 0.001) as well as the caregiver burden caused by this NPS (r_s = 0.40; p < 0.001). Significant correlations of medium magnitude were also found for the number of nights with mobility-related behavior (r_s = 0.43; p < 0.001) and the NPI subscore for sleep & nighttime disorders as well as the care giver burden caused by these disorders (r_s = 0.43; p < 0.001). The magnitude of the correlations between nocturnal mobility-related behavior and other clinical characteristics was small (r_s ranging from −0.09 to 0.23) and not statistically significant.

Table 4: Association of nocturnal mobility-related behavior (number of nights and mean number of nocturnal steps) and clinical characteristics

	Mean number of nocturnal steps		Number of nights with mobility-related behavior	
	rho	***p***	**rho**	***p***
MMSE	0.05	0.657	0.15	0.207
TUG	0.15	0.204	0.23	0.051
Age	0.01	0.963	0.04	0.720
Measurement day	−0.06	0.624	−0.09	0.457
Benzodiazepine (DED) [mg/day]	0.12	0.276	0.17	0.167
Antipsychotics (OED) [mg/day]	0.14	0.239	0.22	0.056
Neuropsychiatric inventory				
Apathy/indifference	0.03	0.827	0.12	0.324
Aberrant motor behavior	0.07	0.581	0.04	0.709
Sleep & night-time behavior disorders	0.39	*<0.001*	0.43	*<0.001*
Caregiver burden caused by sleep & night-time disorders	0.40	*<0.001*	0.43	*<0.001*

Note: Results of the Spearman's rank correlation analyses. Presented are Spearman's rank correlation coefficients (rho). An alpha <0.05 was considered statistically significant. Significant values are presented in italic.
Abbreviations: DED, Diazepam equivalent dose; MMSE, Mini-Mental-Status Examination; OED, Olanzapine equivalent dose; TUG, Timed Up and Go Test.

Discussion

The aim of this explorative study was to investigate the circadian aspects of mobility-related behavior in patients with dementia in acute geriatric psychiatry by analyzing the timing of peak mobility- related behavior, the prevalence of mobility-related sundowning and nocturnal mobility-related behavior and associated clinical characteristics.

The analysis revealed a large variability in the timing of peak mobility-related behavior based on the number of steps, with significant differences between the patients (morningers, mixed types and sundowners) and a high prevalence of nocturnal mobility-related behavior, which was not reflected in the proxy-based assessment of nighttime behavior disorders. Sundowners did not differ from other patients regarding clinical characteristics (global cognitive functioning, motor function, dose of benzodiazepine medication, NPS) except for significant lower doses of antipsychotic medication (OED) compared to morningers. Higher nocturnal mobility-related behavior was associated to more pronounced symptoms of sleep and nighttime behaviors disorders (proxy-rated in the NPI) and higher caregiver burden.

Our results suggest that the timing of the half-hour period of peak mobility-related behavior of patients with dementia in acute geriatric psychiatry during the day occurs in the midafternoon hours. These results coincide with previously reported analyses on quantifying circadian rhythms of agitation in patients with dementia.[5,10] The timing of maximum activity derived from wrist-actigraphy by Martin and colleagues (2:55 PM; range: 9:00 AM to 11:54 PM) is similar to the timing of the 30-minute active period in our study (2:37 PM; range: 3:25 AM to

9:30 PM). Cohen-Mansfield investigated the temporal patterns of agitation via direct observation in nursing home residents with dementia.[10] She observed the highest physical agitation at approximately 4 PM, overlapping with the shift change timing of the nursing staff (3:30 PM). The author hypothesized that staff activities or the lack of those during the shift change might have led to increased agitation in the patients.[10] The temporal characteristics of our active period timing and the change between the morning and the evening shift (2 PM) also fits to the present results. However, the general tendency of maximum mobility-related behavior in the afternoon hours does not characterize all patients. In fact, the analysis revealed a large variability in the timing of daily active periods within the sample, ranging from nighttime to the evening hours, covering a period >18 h.

Our analysis revealed peak gait activity during the afternoon or evening on both days for more than one third of the sample (*n* = 25; 34%), however, we did not find differences in their clinical characteristics compared to the other patients except for significant lower doses of antipsychotics (OED) compared to the morningers. These differences might be caused by the earlier peak of mobility-related behavior within the daily ward routines. During the morning shift, more staff members of the multiprofessional treatment team are working on the wards, which increases the likelihood of recognizing aberrant motor behavior and provides immediate access to physician evaluation and medication adjustment. Conversely, the evening shift, is covered by fewer staff members, leading to a greater chance of overlooking motor behavior symptoms. Additionally, the physicians' workdays usually end during the evening shift. As a result, the attending physicians receive information regarding behavioral symptoms that occur after their shift not until the following morning. By this time, the symptoms are likely no longer in a state of acute manifestation, making adjustments to the medication more challenging.

The revealed differences in antipsychotic medication are contrary to previous findings associating the use sedative medication and antidepressants with higher levels of agitation and activity in the afternoon/evening.[5] However, in the absence of gold-standard criteria, different methods of behavioral observations and a large variety of ordinal scaled assessment tools are applied to assess sundowning behavior. In their recent review, Boronat and colleagues reported the prevalence of sundowning behavior in patients with dementia to be ranging from 2.4% to 82%, depending on the criteria applied to assess the symptoms.[6] The methodological heterogeneity complicates the interpretation of our results and prevents meaningful comparisons of prevalence and clinical characteristics between studies.[6]

An accurate and clinical applicable assessment method to objectively quantify the circadian aspects of mobility-related behavior could contribute to a better understanding of aberrant motor behavior such as the sundowning phenomenon. Ideally, a clinical applicable assessment method requires little time and effort for training, is easy to administer, provides sensitive outcome measures that are easy to understand by a multi-professional treatment team as well as patients and their caregivers and which can be used across all health care sectors.[46] Our results show that hybrid motion sensor-data enable to objectively quantify the timing of peak mobility-related behavior based on the number of steps. Furthermore, hybrid motion sensor technologies enable an accurate assessment of sedentary behavior.[23,37] Assessing the diurnal timing and patterns of sedentary behavior (inactive period) could further contribute to a better understanding of sundowning behavior.[47]

Even if the psychometric properties of this analysis approach still need to be demonstrated, the active period analysis may offer a clinical applicable approach to assess the individual circadian aspects of mobility-related behavior in patients with dementia: Devices to continuously monitor the number of steps, are comparably cheap and easy to use. The step count is a metric that is easy to understand[48] and offers the possibility to derive personalized interventions (e.g., walking interventions with personalized step count goal). Additionally, quantifying the number of nocturnal steps in patients with dementia can provide valuable and detailed information such as the amount of nocturnal mobility-related behavior, which cannot be obtained within clinical routine protocols and proxy-based ratings (e.g., NPI). Positive correlations of medium magnitude were found between the number of nocturnal steps and the professional caregiver ratings of sleep & nighttime behavior disorders as well as the caregiver burden caused by the latter symptoms, indicating the association of objectively measured amount of nocturnal mobility- related behavior and severity of sleep & nighttime disorders rated by professional caregivers as well as their caregiver burden. However, our analysis revealed nocturnal mobility-related behavior in over 50% of the patients (n = 39), whereas proxy-based ratings revealed sleep and night-time behavior disorders in only 26% (n = 19), underestimating the appearance of nocturnal wandering. A previous investigation found an even higher prevalence of wrist accelerometry-based nocturnal mobility-related behavior (67%) in nursing home residents suffering from dementia.[28] The patients with dementia in long-term care only took about one fifth of the nocturnal steps, compared to the average number of nocturnal steps assessed in the present study. The large difference in the results might be explained by different settings and assessment approaches. The present study included patients in acute dementia care, who were admitted to hospital for the treatment of exacerbated of NPS including circadian rhythm-related disorders. Secondly, Moyle and colleagues used wrist-worn accelerometry and a period of only 24 h to monitor the number of steps taken.[26] Previous research showed that this assessment approach lacks accuracy in the detection of steps.[49,50] Since nocturnal wandering means a great burden for patients, fellow patients, as well as professional and informal caregivers, it requires an accurate assessment as well as targeted interventions and their evaluation. A clinical applicable approach to quantify nocturnal mobility-related behavior in patients with dementia promises an improved identification of nocturnal wanderers, who might remain undetected in proxy-based ratings (e.g., NPI) and clinical routines.

An analysis and interpretation of this study and its results should consider the following limitations: Firstly, a measurement period of 48 h is relatively short to analyze circadian patterns. Furthermore, we assessed the timing of peak mobility-related behavior during the day (30-minute period of peak gait activity) but did not investigate the distribution of the number of steps within the day. Hence, the present results do not allow to draw conclusions regarding circadian rhythms of mobility-related behavior in dementia. Secondly, we chose the lower back-worn motion sensor over the commonly used wrist-worn actigraphy, and corresponding Rest-Activity-Rhythm analyses (RAR) based on activity counts. This methodological difference to previous studies limits the comparability of the presented results. However, using hybrid motion sensors enables the assessment of performed activity types. Mobility-related behavior (e.g., assessed as steps or other gait variables) can be distinguished from sedentary behavior and other activity types. Activity counts, on the other hand, have no precise meaning per se. They need to be converted to more relevant constructs, typically based on intensity using cut-point methods or calibration equations.[51] Future studies should further investigate how data on mobility-related and sedentary behavior could contribute to a better understanding of circadian motor behavior. Thirdly, nocturnal activity was analyzed between 10 PM and 7 AM. It is possible that this period does not fit the natural rhythms of all patients. Especially with ageing, the end of the night shifts towards the early morning hours, so that a delayed end of the night at 7 AM might have led to overestimations of nocturnal activity. We chose this time period to define the night period according to shifts of the nursing staff and the daily routines on the wards. Fourthly, the analysis of nocturnal mobility-related behavior was based on periods of more than 15 min, to exclude mobility-related behavior during toilets trips. The period for trips to the bathroom was chosen based on the nursing staffs' experience but might be overestimated for some patients. Hence, the already high rate of nocturnal activity may still be underestimated. Future analyses of nocturnal mobility- related behavior should include sensitivity analyses with shorter periods for trips to the bathroom. Lastly, the descriptive statistic of this explorative analysis includes extreme values and outliers to represent the whole range of mobility-related behavior in patients with dementia in acute geriatric psychiatry care.

Conclusion

This is the first study investigating circadian aspects of mobility- related behavior in patients with dementia using hybrid motion sensing technology. Analyzing circadian aspects of mobility-related behavior may have the potential to provide clinically applicable and 3 Even though the clinical validity of this approach needs to be evaluated, the active period analysis may offer insights into the individual circadian aspects of mobility- related behavior in patients with dementia. Data on the individual timing and intensity of mobility-related behavior (e.g., nocturnal number of steps), and potentially sedentary behavior in patients with dementia could be used to derive, apply, and evaluate personalized interventions using physical activity as circadian zeitgeber.[52] Interventions scheduled to the individual circadian aspects of mobility-related behavior, for example, walking sessions in the afternoon[53] or breaking-up long periods of sedentary behavior[54] are promising non- pharmacological approaches to stabilize circadian motor behavior in dementia.[55]

Analyzing the circadian aspects of mobility-related behavior may help to improve the early detection of disruptions of circadian motor behavior and the tailoring of personalized treatment to enhance outcomes for patients and caregivers.

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Chapter 5

Intervention approaches in geriatric healthcare

Physical Activity Monitoring-Based Interventions in Geriatric Patients: A Scoping Review of Intervention Components and Clinical Applicability

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Objective To identify and analyze the components applied in interventions using physical activity (PA) monitoring in geriatric patients and determine their feasibility and applicability.

Methods A systematic search in six databases (PubMed, Embase, SPORTDiscus, CINAHL, Web of Science, and GeroLit) was conducted to identify studies reporting interventions that included the application of a PA monitor in adults aged ≥ 60 years with a clinical diagnosis. PA monitor interventions were analyzed regarding their feedback, goal-setting and behavior change technique (BCT) components. To determine the feasibility and applicability of interventions, the participants' adherence to the intervention, their experience as well as adverse events were analyzed.

Results Seventeen eligible studies, applying 22 interventions, were identified. Studies included a total of 827 older patients with a median age of 70.2 years. In thirteen interventions (59%), the PA monitor was embedded in a structured behavioral intervention, an indication-specific intervention or usual care. Most frequently applied intervention components were goal setting and self-monitoring (*n* = 18), real-time PA monitor feedback complemented by feedback from the study team (*n* = 12), use of further BCTs (*n* = 18), and regular counseling with the study team (*n* = 19). Comprehensive information on the participants' intervention adherence and experience were reported for 15 (68%) and 8 (36%) interventions, respectively.

Conclusion The components included in PA monitoring-based interventions varied considerably especially regarding the extent, frequency, and content of feedback, goal setting and BCTs counseling. Future research should evaluate which components are most effective and clinically applicable to promote physical activity in geriatric patients. To be able to precisely analyze the effects, trials should seek to report details on intervention components, adherence and adverse events, while future reviews may use the findings of this scoping review to conduct analyses with less heterogeneity in study characteristics and intervention strategies.

Keywords Physical activity tracker, Wearables, Older adults, Medical condition, Personalized treatment

Introduction

Regular physical activity (PA) is a key aspect in the prevention and management of chronic diseases and functional decline in aging [1]. A poor health status is one of the most important determinants of and self-perceived barrier to physical activity in older adults [2, 3]. Only 40 to 55% of older adults meet the World Health Organization's (WHO) guidelines on PA, recommending 150– 300 min of moderate-to-vigorous aerobic intensity PA throughout a week for substantial health benefits [4]. To prevent progress of disease and disability and thus, preserve independency and health-related quality of life, there is an urgent need for clinically applicable strategies to monitor and effective interventions to promote PA over the continuum of care [5]. These strategies and interventions should be tailored to older adults' individual capability and needs.

Deriving such interventions requires assessment tools that provide reliable and detailed information on habitual PA levels. Historically, recall questionnaires and activity logs have been used to assess PA, however, the estimation of PA levels based on self-report methods are susceptible to several biases [6]. Over the past decade, objective assessment methods including body-worn PA monitors, such as accelerometers and inertial measurement units have become the primary choice to monitor PA. Simultaneously, the rapid advances of information and communication technologies have brought a plethora of consumer grade wearable devices (e.g., pedometers, fitness tracker, and smart watches) to the market. PA monitors can generate various parameters that provide an objective feedback on PA (e.g., number of steps). Their use has been associated with increased physical activity levels [7]. Besides objective feedback on PA, PA monitors promote several behavior change techniques (BCT) such as self-monitoring and goal setting that are frequently used in life-style interventions to facilitate behavioral changes [8–10]. The individual tailoring of PA goals and using real-time PA data monitoring throughout an intervention are important features especially in a population (i.e. older patients) not meeting the PA recommendations [3, 10].

Research on the application of PA monitors to assess and intervene on PA is growing rapidly. Literature reviews indicated a moderate effectiveness of body-worn PA monitors to promote PA in (older) adults [11–17]. Previous reviews have defined no or rather broad inclusion criteria regarding the intervention components, leading to a diversity in intervention strategies [17]. Especially in health care, the PA monitors are often used in combination with other BCT components such as psychoeducation on the positive effects of being active, and behavioral counselling including goal setting and identification of barriers or they are embedded into usual care which in turn often contains BCT components [13, 16, 17]. Further methodological heterogeneity arises from differences in the PA monitor devices [13] and in the frequency, extent, and delivery mode of feedback on PA [17].

Given this methodological heterogeneity, there are currently few reviews that can report consistently on the effectiveness of PA monitor-based interventions in geriatric patients. Better knowledge on the applied intervention components is required to be able to conduct consistently focused reviews on the effects of PA monitor-based interventions in geriatric patients and to identify promising intervention approaches for clinical application. For the latter, aspects concerning the feasibility of interventions are also of interest, such as adverse events, as well as the participants' adherence and experience with the intervention [18].

Therefore, the objective of this scoping review is to identify and analyze the components applied in PA monitoring based interventions in geriatric patients. We seek to determine their feasibility in order to identify promising intervention approaches and to guide a way towards consistently focused research on the effects of interventions using PA monitoring in geriatric patients. This review aims to identify and analyze the following components of interventions: (1) the PA monitors applied (2) whether the PA monitor component was used in combination with other interventions (e.g., indication-specific, behavioral, usual care), (3) the frequency, extent, and delivery mode of feedback on PA (4) whether and how PA goals were personalized based on PA data from the PA monitor, and (5) the BCT components applied. In order to determine the feasibility and clinical applicability of interventions, adverse events as well as the participants' adherence to and experience with the intervention were analyzed.

Methods

A protocol of this scoping review has been registered in the PROSPERO database (CRD42020203954). The reporting has been conducted according to the PRISMA extension for scoping reviews [19].

Eligibility criteria

The eligibility criteria were specified according to the PCC (participants, concept, context) approach for scoping reviews [20].

Participants

Studies enrolling participants aged ≥ 60 years and with a confirmed clinical diagnosis of any medical condition according to the International Statistical Classification of Diseases (ICD-10) [21] or the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) [22] were eligible.

Concept

Studies were included if the intervention included any kind of PA monitor (e.g., pedometer, accelerometers, or smartphones) and participants received objective feedback on their PA (e.g., number of steps) based on data from the PA monitor. Studies were excluded if no out- comes on PA were reported.

Context

No in-/exclusion criteria regarding cultural/subcultural factors, geographic location, specific racial as well as gender-based interests or a specific setting were applied.

The language of included studies had to be English or German, thus studies reporting in any other language were excluded. No restriction of publication date was applied.

Search methods for identification of studies

A systematic search strategy was developed using preliminary searches and relevant publications. Relevant keywords and MeSH/ Thesaurus terms were identified to delimit (1) the population of interest and (2) the PAM intervention and (3) the outcome targeted by the intervention. Finally, the search strategy covered a combination of the following keywords and related terms for: ‘geriatrics’, ‘activity tracker’, ‘physical activity’ and ‘health-related outcomes’. The full search strategy can be found in the appendix.

The final systematic search was conducted on May 1st, 2022. The following databases were searched: PubMed, Embase, SPORTDiscus, CINAHL, Web of Science, and GeroLit. Additional studies were obtained by hand searching the reference lists of relevant reviews. Furthermore, international experts in the field of research were contacted and asked to recommend additional articles and ongoing projects they knew and would fit the research question.

Study selection and data extraction

Identified studies were imported into rayyan, a web and mobile app for collaborative work on systematic reviews [23]. Three authors (HS, LS & RT) screened titles and abstracts independently. Disagreements were solved by discussion before full-text assessments. Screening of full texts and data extraction were performed independently by two authors

(LS & RT). Diverging assessments were solved by discussion with the last author (TF).

The following data items were extracted: author, year of publication, country, sample characteristics (sample size, age, clinical diagnosis and setting) and intervention components based on the template for intervention description and replication (TIDieR) checklist [24]. If one study included two or more PA monitor-based intervention arms, we checked if participants of both arms received any kind of feedback based on data from the PA monitor. If so, data were extracted for all intervention arms to which this applied. BCTs were assessed based on the taxonomy of behavior change techniques by Abraham and Michie [25].

To determine the feasibility and applicability of the PA monitor-based interventions, information on adverse events and qualitative feedback on the participants' adherence (e.g., adherence to sensor usage and compliance with PA goals) and experience with the intervention were extracted.

Analysis

In order to be able to compare the applied interventions, their components were grouped into categories as shown in Table 1 and the frequency of interventions was assessed for each component. Similarities in the components of included interventions were investigated based on the UpSet plot analysis [26]. The UpSet plot analysis employs a scalable matrix-based visualization to show intersections of data sets and their size [27]. It was generated using the UpSetR package [27] in RStudio 1.4.1106 for macOS [28]. The implementation of the intervention components as well as results regarding the participants' adherence, experience, and adverse events were analyzed in a narrative review.

Table 1: *Overview of categorization of intervention components*

Component		Yes/No
Intervention	PA monitor as main intervention component	
	Additional to usual care, indication-specific intervention (e.g., weight-loss program) or structured behavioral intervention	
Device	Pedometer (limited to the assessment of steps during walking)	
	PA monitor (enable to assess other activities)	
	Consumer grade device	
	Research grade device	
	Use of corresponding app or web platform	
Main PA target	Steps per day	
	time of walking/light intensity PA per day	
	Sedentary time per day	
Goal-setting	Fixed goals (e.g., 7.000 steps/day)	
	Based on individual PA data (e.g., baseline step count)	
	Goal-setting standardization	
	Tailoring during the intervention	
Self-monitoring	Using PA monitor	
Feedback	By PA monitor/App only	
	Additional feedback provided	
	Feedback only provided by coach	
	Frequency (daily, (≤ once per week, > once per week)	
BCTs	Use of other BCT components besides feedback, goal setting and self-monitoring	
BCT counseling	Individual or group-based	
	Mediation mode (face-to-face, telephone or other)	
	Frequency (≤ once per week, > once per week)	

BCT behavior change technique; PA physical activity

Results

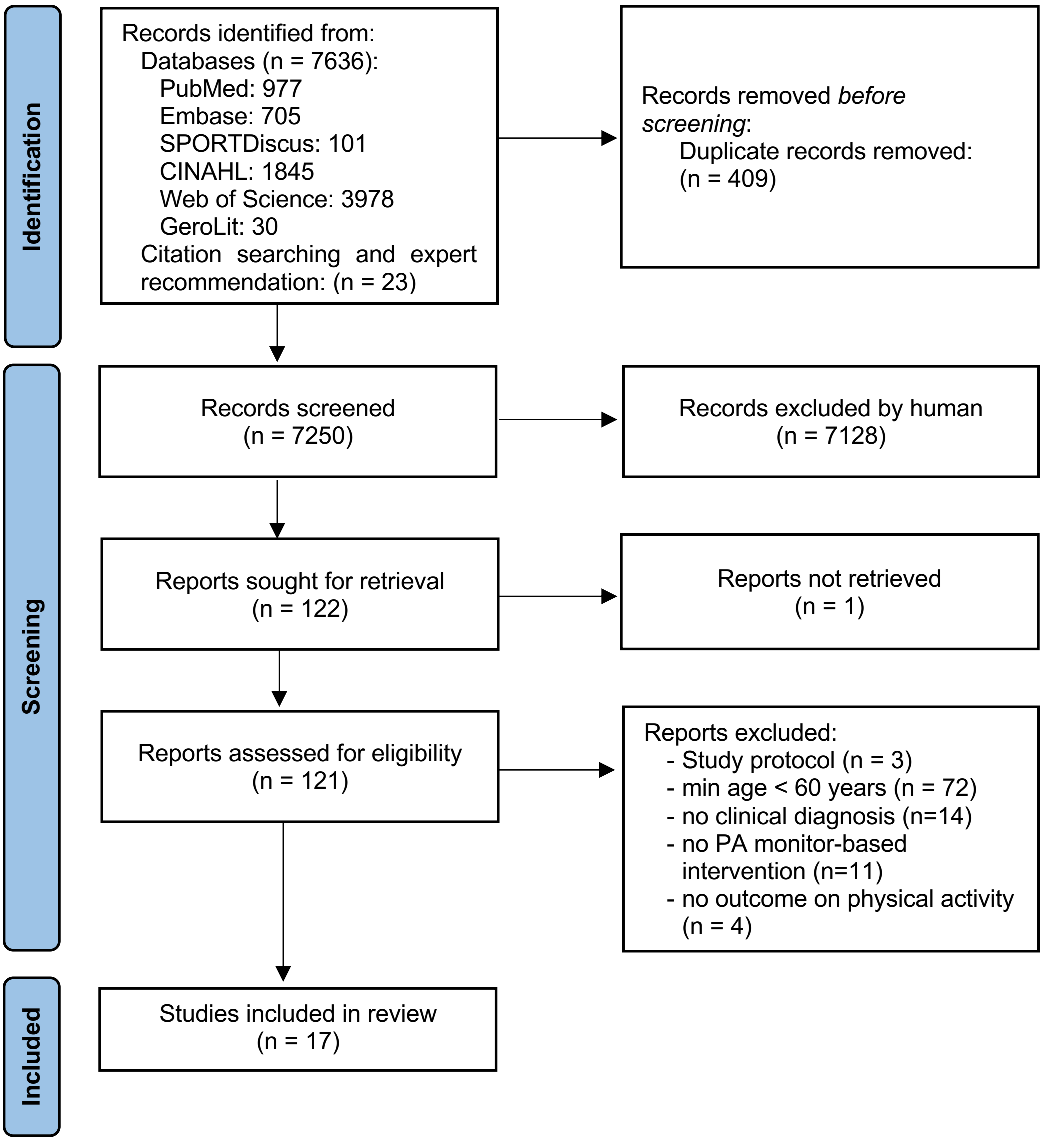
Seventeen studies were included [29–45]. The study selection is illustrated in Fig. 1.

Characteristics of included studies

A summary of the included studies is provided in Table 2. The majority of the included studies (n = 13, 77%) were published within the past five years. Eleven of the selected studies were RCTs [29, 31–33, 35, 37–39, 42, 45, 46] and six were non-randomized intervention trials [30, 34, 36, 40, 43, 44].

The total number of participants was 827, however, the studies varied considerably with regard to the number and characteristics of participants included. The median sample size was 34 participants per study. Peel and colleagues (2016) included the highest number of participants (n = 270). The majority of the studies (n = 14, 82%) included participants with a specific clinical diagnosis [29–31, 33, 35, 36, 38–40, 42–46]. The trials included patients with osteoarthritis [29, 39, 40], obesity [35, 38], chronic obstructive pulmonary disease (COPD) [33, 43], Morbus Parkinson [30], chronic kidney disease [31], chronic heart failure [36], kidney transplant recipients [41], and mild cognitive impairment [44]. The participants of two studies were cancer survivors [42, 45]. Three studies did not focus on a specific indication but included patients with various medical conditions [32, 34, 37]. In eleven studies, a home-based intervention in community-dwelling patients was implemented [30, 32, 33, 36, 38–42, 44, 45]. In two studies, the PA monitor-based intervention was conducted in an outpatient setting [31, 34] and three studied conducted the intervention during inpatient treatment [29, 37, 43]. The setting was not clearly specified in one study [35].

Figure 2: *Flow of study selection process*



Intervention components

The intervention components used in each of the included studies are presented in Table 3. Four studies included two relevant intervention arms that were included as separate interventions [31, 34, 41, 42, 45]. Hence, a total of 22 interventions were included in the analysis. Table 4 shows the frequency of intervention components used in the included studies.

Table 2: *Summary of the characteristics of included studies (n=17)*

Characteristic	Number of studies (%)
Design	
RCT with parallel group design [29,31–33,35,37–39,41,42,45]	11 (65)
Non-randomized study of intervention [30,34,36,40,43,44]	6 (35)
Participant diagnoses	
Cancer survivors [42,45]	2 (12)
Chronic heart failure [36]	1 (6)
Chronic kidney disease [31]	1 (6)
Chronic Obstructive Pulmonary Disease [33,43]	2 (12)
Kidney transplant recipients [41]	1 (6)
Obesity [35,38]	2 (12)
Osteoarthritis [29,39,40]	3 (18)
Mild Cognitive Impairment [44]	1 (6)
Morbus Parkinson [30]	1 (6)
More than one clinical indication [32,34,37]	3 (18)
Setting	
Community-dwelling [30,32,33,36,38–42,44,45]	11 (65)
Outpatient [31,34]	2 (12)
Inpatient rehabilitation/hospital [29,37,43]	3 (18)
No information [35]	1 (6)
Participant characteristics	**Median (range)**
Median sample size	34 (10 to 270)
Median age in studies	70.2 (64 to 81.5)
Median body mass index in studies [29,31,33–39,42,43]	28.4 (21.9 to 35.4)
Median percentage of male participants in studies	44.0 (5 to 100)
Median baseline daily step count [29–31,34–36,38–43,45]	5016 (3034 to 9516)

RCT Randomized Controlled Trial. The reported median of mean values is unweighted in relation to study size or reporting precision.

PA monitor-based intervention component

In nine interventions a body-worn PA monitor and BCTs facilitated by the PA monitor (i.e., feedback, goalsetting, self-monitoring) were used as main intervention strategy [31, 32, 34, 39, 41, 42, 44, 45], whereas in 13 interventions the PA monitor-based component was embedded into usual care, an indication-specific intervention and/ or combined it with a structured behavioral intervention [29, 30, 33–38, 40–43, 45]. Nine interventions used a pedometer [29–33, 35, 36, 39] and 13 interventions a PA monitor that was not limited to the assessment of walking activity [29, 34, 37, 38, 40–43, 45].

Feedback and self-monitoring

In 16 interventions, steps per day were used as feedback parameter [29–34, 36, 39–41, 44, 45]. Four interventions addressed sedentary time [38, 42, 43] and two studies walking time [35, 37]. In 19 interventions participants received real-time feedback from the body-worn PA monitor [30, 31, 33–36, 38–40, 44, 45]. The participants of two interventions, only received the real time feedback from the body-worn PA monitor [31, 34]. In ten interventions, participants were provided with access to device-associated software applications (e.g., Up by Jawbone™, Fitbit by Fitbit, Inc. or Withings Health Mate by Withings) [30, 32, 40–42, 44, 45], that complemented the real time feedback from the PA monitor. The participants of 12 interventions additionally received feedback from the study team [30, 31, 33–36, 38–40, 44, 45], mostly delivered face-to-face [30, 31, 33, 35, 38, 39]. The participants of three interventions had no access to real time feedback by the PA monitor or a corresponding application and received feedback on their PA only by the study team [29, 37, 43]. The frequency of feedback provided from the study team ranged from daily to monthly (Table 4).

Self-monitoring was applied in 18 interventions. In the three interventions that used research grade PA monitors (i.e., ActivPal without display), no self-monitoring was applied [29, 37, 43]. One intervention, using a consumer-grade PA monitor without display (i.e., Jawbone Up band), did not provide participants with access to the device-corresponding application and hence self-monitoring was not applied [38].

Goal setting

In 16 interventions, any kind of goal setting were used [29–31, 33–39, 41–43, 45]. In three interventions fixed overall goals were set, regardless of the results of the PA monitor measurements [31, 33, 38]. Participants of Hiraki and colleagues [31] as well as Kawagoshi and colleagues [33] were instructed to reach a step count goal of 8000 – 10,000 steps per day, while Rosenberg and colleagues [38] set the reduction of daily sedentary time by 60 min per day as overall goal for every participant. In six interventions the overall goal was individualized by adding a fixed number of steps [34, 36, 42] or a percentage [35, 39] to the participant's baseline step count. In 13 interventions PA goals were tailored to the participants capability during the intervention [29, 30, 34, 35, 37–39, 41–43, 45]. In 8 of these 13 interventions, PA goals were tailored based on the data measured by the PA monitor by adding a certain percentage or number to the participant's step count of the previous days [29, 35, 39, 45]. In five interventions PA goals were tailored individually by the study team [30, 37, 41].

Other BCT components

Besides feedback, self-monitoring, and goal setting, the following BCT components were identified (listed by frequency in descending order): social support and/ or comparison, specific instructions, use of cues and prompts, general encouragement, barrier identification, education, use of follow-up prompts, rewards, time management, motivational interviewing, identification as a role model, stress management and self-talk. In 18 interventions one or more of these BCT components were used (Table 3) [29, 30, 33–45]. Four interventions did not use BCT components [31, 32, 34].

Table 3: Intervention characteristics of included studies

	Intervention strategies				**BCT components** **Feedback**			**Self-mnt.**	**Goal Setting**		**Other BCTs**		
Ref.	Compo-nents	PA monitor	App	Parameter	How	Mode	Frequency of delivery		Overall	Tailoring	Compo-nents	Mode	Frequency of delivery
Talbot et al. 2003	PA monitor	New Lifestyles Digi-walker SW-200	no	steps	real time+ stud.team	face-to-face	weekly	applied	30% ↑ of steps/day from baseline	10% ↑ of steps/day every 4 weeks	FP	face-to-face	monthly
Nicklas et al. 2014	PA monitor +behav.int +ISI	Lifecorder Plus	no	Walking time	real time+ stud.team	face-to-face	weekly	applied	20% ↑ in volume of light PA from baseline	initially 10% ↑ in volume of light PA, further ↑ throughout the intervention	BI+CP+ RM+GE+ SC+FP	face-to-face	weekly
Hiraki et al. 2017	PA monitor	Kenz Lifecorder EX	no	steps	real time+ stud.team	face-to-face	bi-monthly	applied	8000-1000 steps/day	not applied	not applied	na	na
Hiraki et al. 2017	PA monitor	Kenz Lifecorder EX	no	steps	real time	na	na	applied	not applied	not applied	not applied	na	na
Brandes et al. 2018	PA monitor +usual care	Step Activity Monitor 3.0	no	steps	stud.team	face-to-face	twice in a week	not applied	not applied	5% ↑ of steps/day compared to previous 3-4 days	CP+GE+ SI+SC+ FP	face-to-face	2x/week
Rosenberg et al. 2020	PA monitor +behav.int	Jawbone UPband + ActivPal	no	sedentary time	real time+ stud.team	face-to-face	tri-weekly	not applied	60 min ↓ sitting time per day	individually	BI+CP+ SC+MI+ GE+SI	face-to-face& Tele-phone	tri-weekly
Peel et al. 2016	PA monitor +usual care	ActivPal	no	walking time	stud.team	face-to-face	daily	not applied	not applied	individually	GE+SC+ FP	face-to-face	weekly
Janevic et al., 2020	PA monitor	Fitbit Zip	yes	steps	real time+ app	na	na	applied	not applied	not applied	not applied	na	na
Kawagoshi et al. 2015	PA monitor +ISI	Lifecorder Ex	no	steps	real time+ stud.team	face-to-face	monthly	applied	8000 steps/day	not applied	SM	face-to-face	monthly
Pinto et al. 2021	PA monitor	Fitbit Charge 2	yes	steps	real time+ stud.team +app	message	bi-weekly	applied	not applied	2000 steps/week:20%↑ 3000 steps/week:15%↑ 4000 steps/week:10%↑ >5000 steps/week:5%↑	CP+SI+ RW+SC	App	by choice
Pinto et al. 2021	PA monitor	Fitbit Charge 2	yes	steps	real time+ stud.team +app	message	bi-weekly	applied	not applied	2000 steps/week:20%↑ 3000 steps/week:15%↑ 4000 steps/week:10%↑ >5000steps/week:5%↑	SI+RW+ SC	App	by choice

	Intervention strategies				BCT components Feedback			Self-mnt.	Goal Setting		Other BCTs		
Ref.	Components	PA monitor	App	Parameter	How	Mode	Frequency of delivery		Overall	Tailoring	Compo-nents	Mode	Frequency of delivery
O'Brien et al. 2021	PA monitor + behav.int	Fitbit Charge 2	yes	steps	real time+ app	na	na	applied	not applied	individually	E+BI+CP +SC+TM +GE+SI+ FP	group face-to-face	monthly
O'Brien et al. 2021	PA monitor	Fitbit Charge 2	yes	steps	real time+ app	na	na	applied	not applied	not applied	E+SC+ FP	group face-to-face	monthly
Blair et al. 2021	PA monitor	Jawbone Up 2	yes	sedentary time	real time+ app	na	na	applied	↓ sedentary time by ↑ of light PA	↑ of > 3000 steps/day from baseline	E+CP+SI	Tele-phone	twice
Blair et al. 2021	PA monitor +behav.int	Jawbone Up 2	yes	sedentary time	real time+ app	na	na	applied	↓ sedentary time by ↑ of light PA	↑ of > 3000 steps/day from baseline	E+BI+CP +SC+GE +SI	Tele-phone	monthly
Morey, et al. 2019	PA monitor	Wrist-worn PA tracker	no	steps	real time+ stud.team	Telephone	weekly	applied	not applied	↑ of > 100 steps/day from to baseline	E+GE	Telep-hone	weekly
Morey, et al. 2019	PA monitor	Wrist-worn PA tracker	no	steps	real time	na	na	applied	not applied	not applied	not applied	na	na
Colón-Semenza et al. 2018	PA monitor +behav.int	FitBit Zip	yes	steps	real time+ stud.team +app	face-to-face	weekly	applied	not applied	individually	E+BI+SC +MI+GE +SI+RW +SC	face-to-face	weekly
Okwose et al. 2019	PA monitor +behav.int	Omron Health care	no	steps	real time+ stud.team	Telephone	weekly	applied	↑ of 2000 steps/day from baseline	not applied	BI+CP+ SC+GE+ SI	Tele-phone	weekly
Zaslavsky et al. 2019	PA monitor +behav.int	Fitbit Charge 2	yes	steps	real time + stud.team + +app	message	weekly	applied	not applied	not applied	CP+RM+ MI+SI+ RW+FP	Tele-phone	not specified
Nickerson et al. 2021	PA monitor	Whithings Activé	yes	steps	real time + stud.team	not specified	not specified	applied	not applied	not applied	SC+TM+ GE	Tele-phone	bi-weekly
Wshah et al. 2022	PA monitor +usual care +behav.int	activPAL	no	sedentary time	stud.team	face-to-face	weekly	not applied	↓ sedentary time by ↑ of light PA	individually	E+BI+CP +SC+ST +TM+GE +SI+FP	face-to-face	once

App – application; BCT – Behavioral change technique; behave.int – structured behavioral intervention; BI - Barrier identification; CP – Use of cues and prompts; E – Education; FP – Follow-up prompts; GE – general encouragement; ISI – Indication-specific intervention; MI – motivational interviewing; na – not applicable; PA – physical activity; RM – Role model; RW – Rewards; SC – Social support/ comparison; Self-mnt. – Self monitoring; SI – Specific instruction; SM – Stress management; ST – Self-talk; stud.team – study team; TM – Time management;

***Table 4:** Frequency of the components used in the interventions (n=22) based on the Template for Intervention Description and Replication (TIDieR)*

TIdieR Items		Intervention components	Frequency in interventions (%)	
Mater-ials		**Device**		
		Pedometer [29–33,35,36,39]	9	(41)
		Physical activity monitor [34,37,38,40–45]	13	(59)
		Use of device-corresponding application [30,32,40–42,44,45]	10	(45)
Procedure		**Intervention components**		
		Physical activity monitor as main intervention component [31,32,34,39,41,42,44,45]	9	(41)
		Embedded in usual care [29,37,43]	3	(14)
		Combined with an indication-specific intervention [33,35]	2	(9)
		Combined with a structured behavioral intervention [30,35,36,38,40–42]	8	(36)
		Target parameter		
		daily number of steps [29–34,36,39–41,44,45]	16	(73)
		daily walking time/ light physical activity intensity [35,37]	2	(9)
		daily time spent sedentary [38,42,43]	4	(18)
		Goal setting [29–31,33–39,41–43,45]	**16**	**(73)**
	Tailoring	Individualized [29,30,34–37,39,41–43,45]	13	(59)
		Tailored during the intervention [29,30,34,35,37–39,41–43,45]	13	(59)
	How	**Feedback on physical activity**		
		only real-time from physical activity monitor/ App [31,32,34,41,42]	7	(32)
		Physical activity monitor/App & feedback from study team[30,31,33–36,38–40,44,45]	12	(55)
		Only from study team [29,37,43]	3	(14)
	How much	**Frequency of feedback from study team**		
		Daily [37]	1	(5)
		≥ once per week [30,31,33–36,38–40,43,45]	12	(55)
		< once per week [29]	1	(5)
		Not specified [44]	1	(5)
		Self-monitoring using physical activity monitor [30–36,39–42,44,45]	**18**	**(82)**
		Use of other behavior change techniques [29,30,33–45]	**18**	**(82)**
		Barrier identification [30,35,36,38,41–43]	7	(32)
		Use of cues and prompts [29,35,36,38,40–43,45]	10	(45)
		Education [30,34,41–43]	7	(32)
		Use of follow-up prompts [39–41,43]	5	(23)
		General encouragement [29,30,34–37,41–44]	10	(45)
		Motivational interviewing [30,38,40]	3	(14)
		Role model [35,40]	2	(9)
		Rewards [30,40,45]	4	(18)
		Social support/ comparison [29,35–38,41–45]	13	(59)
		Specific instruction [29,30,36,38,40–42,45]	11	(50)
		Stress management [33]	1	(5)
		Self-talk [43]	1	(5)
		Time management [41,43,44]	3	(14)
		Mode of behavior change technique mediation [29,30,33–40,42–45]	**18**	**(82)**
	How	Individual [29,30,33–40,42–45]	16	(73)
		Group-based [41]	2	(9)
		Face-to-face [29,33,35,37–39,41,43]	10	(45)
		Telephone [34,36,38,40,42,44]	7	(32)
		only via application [45]	2	(9)
	How much	**Frequency of behavior change technique mediation**		
		≥ once per week [30,33–44]	14	(64)
		< once per week [47]	1	(5)
		by choice [45]	2	(9)
		Not specified [48]	1	(5)
	who	**Behavior change technique mediated by**		
		Study team [29,34–36,38,40–44]	12	(55)
		Healthcare staff [33,37,43]	3	(14)
		Peer group [30]	1	(5)
		Application [45]	2	(9)
	where	**Setting**		
		Home-based [30–33,36,39–42,44,45]	18	(82)
		Hospital/ rehabilitation clinic [29,37]	3	(14)
		not specified [49]	1	(5)

Similarities of the interventions

The upset plot analysis of similarities of the interventions revealed a variety of component combinations between the interventions. Thirteen interventions combined the following components: regular counseling by the study team (e.g., for feedback on PA and/or BCT delivery), use of other BCTs than goal setting, feedback and self-monitoring, goal setting, and feedback on PA from the study team [29, 30, 33–39, 41–43]. In three out of these interventions, the PA monitor was used as the main intervention component [34, 39, 42]. In all three of these interventions individualized goals were applied. Two out of the three interventions applied face-to-face contacts to deliver feedback and/or BCTs [34, 39]. Ten interventions embedded the PA monitor component into another intervention (e.g., usual care) [29, 30, 33, 35–38, 41–43]. Seven out of these ten interventions applied individualized PA goals [30, 35–37, 41, 42] and seven interventions delivered feedback and/or BCTs face-to-face [29, 33, 37, 38, 41, 43]. Four out of the seven interventions used both individualized PA goals and face-to-face contacts to deliver feedback and/ or BCTs [29, 35, 37, 41].

Participants' adherence and experience, adverse events

For most interventions (*n* = 15, 68%) information on adherence to PA monitor usage were reported [29, 33, 35, 37, 39–45]. The median percentage of days participants wore the PA monitor device reported for 9 interventions was 87% [29, 33, 35, 39, 41, 44, 45], ranging from 57% [29] to 99%[44]. Wear times of the PA monitor was reported for 4 interventions [29, 35, 37, 40].

The median wear time per day was 11.5 h per day and ranged from 8.3 h per day [37] to more than 20 h per day [40]. In one study (*n* = 2 interventions) the PA monitor device and application usage were evaluated based on the participants' self-report using the 5-point Likert scale [42]. All participants (*n* = 29) agreed or strongly agreed to have worn the PA monitor (Jawbone Up) on most days of the week, however, 62% of the participants indicated that they ignored the alert from the device and remained seated when reminded to stand up and move [42].

Information on achievement of set PA goals were provided for 4 interventions [33, 35, 39, 43]. The median percentage of days on which PA goals were met was 57%, ranging from 48 to 81%. Wshah and colleagues [43] reported that 73 goals were set over the intervention period, of which 41 (56%) were met.

Information about the occurrence or non-occurrence of adverse events were available for 8 interventions [30, 31, 36, 38, 42]. Only Rosenberg and colleagues [38] reported that 10% of the participants experienced mild skin irritation from the PA monitor device (Jawbone Up band).

Participants' satisfaction with the intervention components was analyzed in 8 studies [30, 32, 38, 42, 43, 45]. The median proportion of participants who were satisfied with the overall intervention strategy was 89%, ranging from 89% [45] to 92% [38] and was reported for four interventions [38, 43, 45]. Participants' satisfaction with the PA monitor device was reported for four interventions [32, 38, 42]. The median proportion of participants who were satisfied with the PA monitor usage was 79% and ranged from 79% [38, 42] to 96% [32]. Problems with the PA monitor device were reported for three interventions [30, 32, 38]. Twenty-five percent of the participants in the intervention by Janevic and colleagues [32] had problems to synchronize the device (Fitbit Zip) with the corresponding application. One participant (2%) in the intervention of Colón-Semenza and colleagues [30] reported problems in handling the PA monitor device (Fitbit Zip). Four participants (9%) of the intervention described Rosenberg and colleagues [38] experienced the PA monitor (Jawbone UP band) as not helpful and two participants (7%) reported that they did not use the PA monitor. Participants of three interventions were asked, if wearing the PA monitor device made them more aware of their PA level [32, 45]. The reported agreement ratios ranged from 41% [45] to 75% [32]. Participants of three interventions were asked if they would continue to use the PA monitor after the intervention ended [32, 42]. The agreement ratios ranged from 57% [32] to 79% [42].

Discussion

The objective of this scoping review was to identify and analyze the components applied in PA monitoring based interventions in geriatric patients and to assess their feasibility and clinical applicability.

Summary of evidence

In this scoping review we identified 22 interventions in which PA monitors were applied to provide geriatric patients with objective feedback on their PA levels. Our results revealed that the PA monitors were most frequently combined with structured behavioral health interventions, an indication-specific intervention or usual care. Most of the interventions focused on the daily number of steps as target parameter for self-monitoring, feedback and/or goalsetting. Other most frequently applied intervention components were goal setting, adjunct feedback from the study team, the use of further BCTs, and regular counseling with the study team. More than half of the included interventions combined all of the former four components. Despite the overlap in the use of these intervention components, we found differences in their implementation, which will be addressed in the following discussion considering the available findings on feasibility and applicability of the different approaches.

PA monitor and feedback component

A wide range of different PA monitors were applied which vary in their ability to measure PA parameters and to provide corresponding feedback. In 41% (*n* = 9) of the interventions simple pedometers were applied. Pedometers measure walking activity and provide information on related parameters, such as the number of steps (most frequently used) or walking time and distance. Hence, they are essential to programs that recommend a specific step count goal or requiring self-monitoring of daily steps taken. However, the traditional devices (e.g., KENZ Lifecoder EX) often do not enable automatic data transmission, requiring users to manually transcribe data to activity logs which limits their applicability for long-term PA monitoring. Furthermore, the lacking accuracy of simple pedometers in the assessment of steps often lead to overestimations in step counts, which might induce higher effect sizes when compared to accelerometer-based PA monitors [13]. Lacking accuracy is also one reason indicated by older adults preventing the use in their daily lives [47]. Although the present review identified the lowest adherence rates for research grade devices [29, 37], data on the adherence to PA monitor usage were often not reported for pedometer-based interventions [30–32, 36]. In order to fully understand the benefits of PA monitors and to estimate the applicability of single devices, future studies should report consistently on the adherence to PA monitor usage and any barriers leading to non-adherence.

Although pedometers are considered well accepted by older adults because they are usually easier to operate, participants aged more than 60 years also appear to be receptive to using more sophisticated PA monitors and learn to use them quite easily [47]. Such devices, allowing the assessment of other activities not limited to walking and also enabling the assessment of sedentary behavior, were used in 13 interventions (59%). The detailed assessment of physical activity enables to provide users with more comprehensive feedback on health enhancing/ threatening PA behaviors not limited to walking. However, the accuracy of corresponding assessment methods as well as the access to feedback and its delivery mode differ between devices. In three interventions participants wore a research grade PA monitor (e.g., ActivPal), which does not enable to provide the wearer with real-time feedback on PA. Hence, the participants received feedback on their performance only at times when it was provided to them by the study team. On the contrary, patients who received a modern consumer grade PA monitor, i.e., Fitbit Zip or Charge 2, Jawbone UP, Whithings Activé, received detailed real-time feedback on their PA and also had (except in one intervention) access to a software application at their convenience. These applications often provide even more detailed and interactive visualized feedback on various parameters related to PA [10], even those that are not necessarily part of the intervention. Extended feedback (e.g., number of calories burned) might additionally motivate to increase PA; however, the amount and complexity of health-related information can make it difficult for users to understand and interpret the data, leading to feelings of overwhelm. With more activity trackers brought to the market and advances in their features, future studies are needed to investigate how the feedback component should be designed to effectively improve PA and sedentary behavior. Literature reviews should apply more specific inclusion criteria regarding the devices and their feedback options or conduct subgroup analyses for less methodological heterogeneity.

An important issue, that needs to be considered regarding commercially available PA monitors, is that information regarding their psychometric properties (e.g., validity and reliability) is often not available [48, 49] or it is unclear how they were assessed (i.e., was the validation performed in geriatric populations and under real-life conditions by independent parties?) [50]. Furthermore, the data processing and applied algorithms for PA analysis of consumer grade devices are often not accessible due to economic interests of the manufacturer [51]. Within this context, identifying non-wear times is an important aspect that affects all PA monitors in terms of their clinical applicability for assessing and intervening on PA in geriatric health care as misclassifications of non-wear times likely lead to an over or underestimation of PA levels [52].

Compared to recent research grade devices (e.g., the ActivPal), consumer-grade PA monitors enable the self- monitoring of PA, and the device-corresponding applications make it easy to share the objective information on PA, e.g., with institutions in the continuum of care, representing a promising solution for future health care using PA as a vital sign [53]. However, within this context enhancing the oversight of the wearable device industry, providing specific safety regulations to protect the privacy and security of personal data, and clarifying relevant medical responsibilities as well as rights between physicians and patients are crucial aspects that need to be addressed [54].

This might also be the reason why only Peel and colleagues [37] integrated the PA monitor component into the routine care process by discussing patient’s PA levels in the weekly case conference and providing patients and their therapists with daily feedback on PA measured with the ActivPal. None of the interventions conducted in in-patient settings [29, 37, 43] were designed to be continued in the follow-up treatment or to involve the out-patient treatment provider. At this point it is important to mention, that the health status of patients differ across the healthcare sectors (e.g., inpatient setting vs. community dwelling), complicating the implementation of interventions across the continuum of care [5]. However, PA monitors can provide objective feedback on PA (e.g., number of steps) that can be easily understood by the patients themselves and a multiprofessional treatment team across health care sectors. Future studies should investigate how the PA monitor and corresponding feedback could be implemented across the continuum of care.

Personalization of PA goals

Of 16 interventions that used goal setting, 12 interventions applied personalized PA goals that were based on the data from the PA monitor. Especially in geriatric health care, where patients are prone to fail the general PA recommendations, it is important to set measurable, attainable goals [3] and to monitor progress carefully [37]. The continuously assessed data from the PA monitors enables the former and further allows to set goals in line with the patient's previous/current performance and ability level, which have been shown to be important aspects to improve physical activity engagement [55]. However, only less than half of the interventions (8, 44%) used the opportunity to adapt PA goals during the intervention based on the continuous PA data. Furthermore, the personalization approaches ranged from standardized procedures (e.g., adding a percentage of steps to the number of steps per day) [29, 35, 45] to individualized goals without any further details on the goal setting process [30, 37, 41]. Replicating the interventions and applying them in clinical practice requires more detailed information on how PA goals were personalized. Future research should aim to improve the personalized goal setting and to evaluate their effects.

Besides individualizing the amount and volume of PA goals, personally tailored advice regarding its timing and environmental aspects could further help to improve the intervention adherence [56]. Personalized timing of interventions was realized by using the real-time data from the PA monitor within three interventions [38, 42]. In all three interventions the overall aim was to reduce the time spent sedentary using Jawbone Up band and its incorporated *idle alert* function to notify the user on inactivity via a gentle vibration of the wrist band after a user specified time spent inactive. This offers the possibility to deliver the intervention when behaviors occur, that should be prevented – e.g. long periods of sitting time. Sometimes, however, external circumstances do not allow for immediate interruption or change in current behaviors. In all three interventions the alert was set to 15 min [38, 42]. The participants satisfaction with the PA monitor was lowest for the Jawbone UP band [38, 42]. In order to ensure the continued use of the PA monitors, the time limits should be set carefully and based on scientific findings or health guidelines. Furthermore, users could be given the opportunity to mute notifications for limited periods.

BCT components

Eighty-two percent of the interventions (*n* = 18) included the use of one or more BCT components additionally to the BCTs promoted by the PA monitor (e.g., feedback on performance and self-monitoring), indicating the importance of combining the objective feedback from the PA monitor with BCTs. This is in line with the results of the review from

Braakhuis and colleagues [17], who found combinations of one or multiple BCTs in all interventions using objective feedback from PA monitors. Besides feedback on performance and self-monitoring, goal setting, social- support and comparison, general encouragement, specific instructions how to change the behavior (e.g., reduce sedentary time by reducing the time watching TV) and the use of cues and prompts were revealed as BCT components considered important in the present interventions. However, the number of combined BCT components used in the present interventions as well as the frequency of their delivery varied considerably, ranging from none [31, 32, 34] to nine [43] and once during the intervention period [43] to twice per week [29], respectively. Unfortunately, not all interventions clearly indicated which BCT components were used and described their content sufficiently. Hence, BCTs could only be determined approximately making it difficult to draw clear conclusions regarding specific BCT components. It can be assumed that indication-specific interventions (e.g., weight loss programs in obesity) and usual care also incorporate the use of BCTs.

A recent meta-analysis found that neither the frequency of feedback from the PA monitor nor whether goal setting was applied influenced the effectiveness of PA monitors in adults < 65 years, but differences in the population characteristics [57]. The authors indicated that some patient populations (e.g., overweight participants or participants with depression or anxiety) might experience an ambiguous and even counterproductive influence from PA monitor feedback. Research also suggests that BCTs that are effective at increasing PA in younger adults may not be effective for older adults [58]. In order to be able to better understand how and which BCTs are relevant in PA monitor interventions for geriatric patients, future research needs to clearly indicate which BCTs are used and how they are applied (see Blair and colleagues [42] for a positive example).

Consumer grade PA monitors and corresponding software applications contain various BCT components [9, 10], however, the present and previous results [17] show, that they are usually delivered within in-person counseling. Using the BCTs incorporated in PA monitors and corresponding applications in combination with real- time tele-counseling can make behavior change interventions clinically applicable through conservation of resources and improved cost-effectiveness [9]. Further research is needed to determine the most effective intervention strategies, with regard to the amount and type of therapist contact and BCT components for specific patient populations.

The following limitations need to be addressed within this scoping review: Firstly, a conclusive assessment of promising intervention approaches with regard to their feasibility and clinical applicability could not be performed because information on the participants' adherence to and experience with the intervention was rarely reported within the individual studies. Secondly, the number of BCT components applied and their content might not have been assessed completely accurate, as not all interventions clearly indicated in detail which access the participants had to BCTs that were incorporated in the PA monitors and the corresponding applications.

With further advances in the field of information and communication technologies and the popularization of personalized health concepts, wearable devices will inevitably play a greater role in the field of health care and become better integrated into daily lives [59]. The intervention components applied in older adults with chronical conditions so far differ clearly form each other and it seems that the potential of PA monitors with regard to the use of integrated BCTs components and PA-monitor data to personalize interventions has not been exploited to the fullest yet. Modern PA monitors enable the monitoring of activity behavior (physical activity and sedentary behavior) and also sleep continuously over 24 h/day. A more in-depth analysis of the latter two in terms of their interrelation could possibly enable to identify individual activity profiles [60, 61] that could be used to decide whether the participant’s intervention should focus on the improvement of PA or sedentary behavior.

Conclusion

This scoping review gives an overview on the components applied in interventions using PA monitors to provide older adults in geriatric health care with objective feedback on their PA. The overall intervention strategies varied considerably especially regarding the implementation of the feedback and BCT components. Details on adherence and adverse events have often not been reported, limiting the determination of the interventions’ clinical applicability. Future research should focus on determining which intervention components are most effective in improving PA and especially sedentary behavior, investigate the effects of personalized PA goals and how PA-monitor based interventions can be applied over the continuum of geriatric health care. To be able to precisely analyze potential effects, trials should seek to report details on intervention components, particularly which BCTs are used and how they are applied, as well as details on adherence and adverse events. Future reviews may use the findings of this scoping review to conduct analyses with less heterogeneity in study characteristics and intervention components.

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Appendix

PubMed search strategy

Participants	(("Aged"[Mesh]) OR (older adults[tiab]) OR (old adults[tiab]) OR (older adult[tiab]) OR (older people[tiab]) OR (frail elderly[tiab]) OR (senior*[tiab]) OR (elder*[tiab]) OR ("Aged, 80 and over"[Mesh]) OR ("Nursing Care"[Mesh]) OR (Geriatrics) OR ("Geriatric Nursing"[Mesh]) OR ("Frailty"[Mesh]) OR ("Above 60 years"[tiab]) OR (Hospital ward) OR (Clinic) OR (Acute Care) OR (outpatient clinic))
	AND
Intervention	(("Fitness Trackers"[Mesh]) OR ("Accelerometry"[Mesh]) OR (Activity Tracker*[tiab]) OR (Personal Fitness Tracker*[tiab]) OR (Physical Fitness Tacker*[tiab]) OR (monitor*[tiab]) OR (activity monitor*[tiab]) OR (accelerometer based tracker*[tiab]) OR (step monitor*[tiab]) OR (physical activity monitor*[tiab]) OR (step counter[tiab]) OR (pedometer[tiab]) OR (quantified movement[tiab]) OR (movement counter[tiab]) OR (hybrid PA monitor*[tiab]) OR (body worn PA monitor*[tiab]) OR (smartphone application[tiab]) OR (jawbone[tiab]) OR (vivoactive[tiab]) OR (tomtom[tiab]) OR (xiaomi mi band[tiab]) OR (moov now[tiab]) OR (misfit ray[tiab]) OR (nokia go[tiab]) OR (Fitbit[tiab]) OR (Yamax[tiab]) OR (Omron[tiab])) AND ((self reported physical activity[tiab]) OR (personal* activit*[tiab]) OR (individual* activit*[tiab]) OR (individual exercise[tiab]) OR (individual recommendation[tiab]) OR (personal recommendation[tiab]) OR (individual intervention[tiab]) OR (counseling[tiab]))
	AND
Outcomes	(("Quality of Life"[Mesh]) OR ("Exercise"[Mesh]) OR (physical activity[tiab]) OR (functional fitness[tiab]) OR (functional mobility) OR Steps[tiab] OR (steps per day[tiab]) OR pain[tiab] OR ("Activities of Daily Living"[Mesh]) OR ("Housing for the Elderly"[Mesh]) OR (moderate-to-vigorous physical activity) OR MVPA OR (Osteoarthritis) OR (arthroplasty) OR (arthritis) OR (joint replacement) OR (COPD) OR (chronic obstructive pulmonary disease) OR (Cardiac patients) OR (hypertension) OR (vascular diseases) OR (type 2 Diabetes) OR (impaired glucose tolerance) OR (intermittent claudication) OR (overweight) OR (obese) OR (dialysis) OR (breast cancer) OR (cancer) OR (neuromuscular disease) OR (stroke) OR (Parkinson disease) OR (impaired cognitive function) OR (intellectual difficulties) OR (fibromyalgia) OR (polyneuropathie) OR (PNP) OR (sarcopenia))
	NOT
Exclusion of	((healthy older adults) OR (child*) OR (animal) OR (adolescence) OR (young adult))

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Chapter 6

Discussion

The primary objective of this thesis was to evaluate the use of motion sensor-based approaches to assess and monitor physical activity as input into interventions for older adults, particularly in geriatric health care settings.

This aim was achieved by (1) comparing the outcomes of three physical activity assessment methods, (2) developing and evaluating a novel method of analyzing the circadian aspects of mobility-related behavior, (3) exploring how circadian aspects of mobility-related behavior relate to the clinical characteristics of patients with dementia, and (4) providing an overview of the current evidence regarding the components and clinical applicability of physical activity monitoring-based interventions in geriatric medicine.

This chapter will first briefly summarize the key results of the preceding chapters. The subsequent sections will address the following principal areas of discussion: a) how to assess physical activity in older adults; b) clinically applicable physical activity outcomes; c) physical activity and its circadian aspects, d) the role of circadian rhythms in acute dementia care; e) a section on the relevance of analyzing temporal aspects of physical activity; f) personalization of physical activity interventions beyond one-size-fits-all approaches, and g) methodological considerations and critical reflections of the own research activities. The chapter will conclude with an outlook on the role of motion sensor-based physical activity monitoring in health care and implications for future research in physical activity of older adults.

Key findings

In **Chapter 2**, the physical activity levels of 53 community-dwelling older adults were assessed using two simultaneously worn accelerometer-based devices (i.e., actigraph and hybrid motion sensor) and compared. Significantly longer durations for all physical activity intensities were measured with the actigraph compared to the hybrid motion sensor (∆ light intensity: 2:55 h/day; ∆ moderate-to-vigorous intensity: 2:47 h/day). Actigraph-based durations of sedentary behavior were significantly shorter compared to the durations measured by hybrid motion sensor (∆ sedentary behavior: 5:43 h/day). The use of hybrid motion sensors can offer important insights into physical activity levels and types (e.g., sitting, lying) and thus may enhance knowledge regarding mobility-related physical activity and sedentary behavior patterns, while actigraphy appears to not be recommended for this purpose.

The results of an analysis of the circadian aspects of physical activity based on the daily step count of 81 healthy older adults and their comparison between subjective chronotypes were reported in **Chapter 3**. The analysis revealed significantly earlier daytimes of peak mobility-related behavior in individuals characterized as morning types compared to those categorized as intermediate and evening types. The results indicated an association between subjectively rated chronotypes and the timing of peak mobility-related activity in healthy older adults. The timing of peak mobility-related behavior may constitute an innovative approach to monitor changes in physical activity behavior and personalize physical activity interventions.

In **Chapter 4**, the results of an explorative analysis of the timing of peak mobility-related behavior in 73 patients in acute dementia care were reported. The mean start time of peak mobility-related behavior was 2:37 PM, though large variability in timing was found (range: 3:25 AM–9:30 PM). Nocturnal mobility-related behavior was observed in 35 patients (53%), and significantly associated with higher perceived caregiver burden. Analyzing the timing of peak gait activity and nocturnal step count in acute dementia care appears to provide clinically applicable and more detailed information regarding aberrant motor behavior (e.g., sundowning, nocturnal wandering), which might remain unobserved in clinical routine or whose frequency and severity can only be roughly estimated in proxy-ratings.

The scoping review, reported in **Chapter 5**, analyzed the components as well as the feasibility and clinical applicability of interventions reported in 17 studies (22 intervention arms included) that incorporated the use of motion sensor-based physical activity monitoring in geriatric patients. The intervention components varied considerably, particularly in the extent, frequency, and content of feedback, goal setting, and BCT counseling. Future research should seek to identify the components that are most effective and clinically applicable in the promotion of physical activity in geriatric patients. To enable the precise analysis of effects, future trials should include detailed reporting of intervention components, adherence, and adverse events.

How to assess physical activity in older adults

As highlighted in **Chapter 1**, older adults' physical activity behavior differs from other populations in that older adults primarily engage in physical activity at low intensities and sedentary behavior as part of their activities of everyday life (Lindemann et al., 2014; van Schooten et al., 2018; Westerterp, 2008). Thus, the assessment of physical activity in old age requires the reliable measurement of light-intensity activity, mobility-related activities, and sedentary behaviors.

The direct comparison of two commonly used assessment methods (i.e., self-report and actigraphy) with a hybrid motion sensor-based approaches in **Chapter 2** revealed that the physical activity outcomes assessed by the three methods were not comparable (Trumpf et al., 2020). The divergence of the methods' results was most evident for light-intensity physical activity and sedentary behavior (Trumpf et al., 2020). This is in line with previous research suggesting that self-reported durations of light-intensity physical activity and sedentary behavior are particularly prone to measurement error (Allet et al., 2010; Durante & Ainsworth, 1996). Short-term recall questionnaires such as the German Physical Activity Questionnaire (the German version of the widely used International Physical Activity Questionnaire) employed in **Chapter 2** require respondents to recall the frequency and duration of physical activity at a specific intensity or in a particular domain (e.g., transportation, household, leisure) performed in a usual week during the past month. Recalling sedentary behavior and light-intensity activities that are performed as part of everyday life, such as walking to travel from place to place, performing household chores, or gardening (Durante & Ainsworth, 1996), is particularly difficult. This approach allows for a basic and orientational assessment of global physical activity levels, but cannot provide continuous data, necessary for deeper analysis of specific aspects of physical activity and sedentary behavior. Thus, an assessment of physical activity that considers target group-specific and clinically relevant parameters is not achievable with questionnaire-based methods.

Furthermore, this thesis extends existing evidence on the inappropriateness of actigraphy-based approaches to assessing real-life physical activity in older adults. Activity counts, on which actigraphy is based, have no precise meaning per se. They are an aggregate measure of the amount and intensity of activity performed in a given time period (Lee et al., 2023) and are generated by unique, manufacturer-owned algorithms (John et al., 2019). Furthermore, different wear locations—such as hip versus wrist—elicit different counts, which contributes to a lack of standardization. Hence, counts are not comparable across devices and wear locations (Lee et al., 2023). The results presented in **Chapter 2** clarify the extent of the variability across devices through a direct comparison of the time spent at different physical activity intensities as measured by the activity counts of two simultaneously body-worn motion sensors (Trumpf et al., 2020). More important to this thesis, however, is the inability of most actigraphic devices, such as the MotionWatch 8 studied in **Chapter 2**, to provide information on body postures (Liu et al., 2022; Trumpf et al., 2020), causing them to be unable to distinguish light-intensity activities with an MET < 1.5 (e.g., quiet standing) from sedentary activities, or any activity with an intensity < 1.5 MET performed while sitting, reclining, or lying down (Tremblay et al., 2017). This is reflected in the results of **Chapter 2**, which showed substantial differences between activity count-derived and body posture-derived measurements of the duration of light-intensity and sedentary activities. This thesis' results, in combination with the findings of previous research, indicate that an assessment of physical activity and particularly of sedentary behavior based on activity counts is not recommended in older adults.

Although the estimation of time spent performing activities of different intensities is important for understanding the health benefits of physical activity and compliance with physical activity guidelines, this quantification method reduces the high-frequency time-series nature of accelerometer and gyroscope data to basic total scores (e.g., active minutes/day) (Liu et al., 2022). The enormous potential of this rich data source to enable a deeper understanding of the link between physical activityand health has yet to be fully realized. The development of approaches that assess when and how physical activity and sedentary behavior are accumulated throughout the day can add new dimensions to the research of physical activity in older adults beyond the basic parameters of volume and intensity as highlighted in both this thesis and previous findings (F. Liu et al., 2021). This is particularly relevant to the population of older adults, among whom high rates of sedentary behaviors are characteristic.

Clinically applicable physical activity outcomes

The assessment of physical activity requires suitable measurement methods that can be used for scientific purposes as well as in clinical practice to, for example, verify treatment success. Assessment strategies thus need to satisfy requirements regarding their clinical applicability, which, as described in this thesis, combines aspects of the approaches' clinical relevance and practical feasibility. To be clinically useful, the outcomes of physical activity assessments should facilitate evidence-based decision-making, such as the decision-making required to provide targeted physical activity advice. This requires the measurement of physical activity parameters that are relevant to the target group using suitable measurement instruments, which must fulfill certain quality criteria, including the demonstration of sufficient validity and reliability in the target population and setting (Dowd et al., 2018). In addition, assessment approaches should fulfill requirements regarding their practical feasibility, among which is the intelligibility of the assessment's outcomes, a key consideration due to the need for older adults and clinicians without extensive experience in movement and exercise science to be able to interpret and understand physical activity outcomes and corresponding advice. Within this context, the usability of the assessment tool plays a decisive role; tools must be cost-effective, time-efficient, easily learned, and accepted by the target population.

As highlighted in **Chapter 1**, the ability to remain mobile and live independently in old age is a central health concern of older adults and health care systems, making the performance of functional activities such as standing and walking a key construct of physical activity in older adults (Lindemann et al., 2014). Sedentary behavior, on the other hand, has an adverse impact on health. Step count is an intuitive metric to quantify walking activity (Walker et al., 2021), as it captures both light and moderate-to-vigorous activity and thus offers a method for assessing daily physical activity (Kraus et al., 2019). Walking quantity and daily step count play a critical role in preventive medicine, as they are strongly and inversely associated with premature all-cause mortality (Hansen et al., 2020; Paluch et al., 2022); daily walking durations and step count should thus be key targets in physical activity-promoting interventions for older adults (Larsen et al., 2019; Trumpf, Schulte, et al., 2023). Viewed from the perspective of clinical applicability, daily step count is a physical activity outcome that is (a) relevant to the target group of older adults as it is a measure of mobility, (b) accessible in both research and health care contexts, and (c) intuitive and easy to understand. As highlighted in **Chapter 5**, step count tracking is often at the core of interventions to promote physical activity because ubiquitous technology allows individuals to receive immediate feedback on their physical activity levels, which can in turn motivate future activity (Mair et al., 2023). Ultimately, step-based targets offer greater options to populations and individuals for setting physical activity goals and monitoring progress. Such tailored approaches to physical activity promotion that consider individual needs and preferences are likely to be the most promising (Mair et al., 2023).

Alongside mobility-related activities, sedentary behavior makes up the predominant proportion of older adults' daily physical activity (Lindemann et al., 2014; Walker et al., 2021) and is highly associated with health outcomes. As sedentary behavior is specific to activities with low energy expenditure performed in sitting, reclining, and lying postures, the assessment of sedentary behavior relies on the determination of body posture in addition to the estimation of physical activity intensity (Trumpf et al., 2020). Similar to daily step count's intuitiveness as a physical activity outcome, time spent in different body postures may serve as a clinically applicable outcome of sedentary behavior. Daily time spent sitting has been linked to chronic diseases and a higher risk of mortality (Bailey et al., 2019; Katzmarzyk et al., 2009). Prolonged bouts of sitting (> 20 or 30 minutes) in particular appear to be associated with health risks (Biddle et al., 2021; Loh et al., 2020; Saunders et al., 2018) and first national health guidelines have included recommendations to increase breaks from long sitting periods (Buckley et al., 2015; Ross et al., 2020). Interrupting periods of prolonged sitting has increasingly been employed as an intervention target in older adults (Bailey et al., 2023; Blair et al., 2021; Rosenberg et al., 2020; Wshah et al., 2022). Like step count, sedentary behavior can be tracked easily with wearable devices (consumer and research grade), enabling the provision of immediate user feedback when sedentary behaviors such as long periods of sitting occur (Trumpf, Schulte, et al., 2023). Daily step count and sitting time's relevance in older adults' everyday lives, association with health, accessibility, and comprehensibility make these measures clinically applicable target parameters of physical activity behavior in older adults with the potential to be used across the continuum of care. However, despite the value of clinically applicable summary parameters for public health messaging and the measurement of compliance with general physical activity guidelines, this method of assessing physical activity leaves the full potential of device-based physical activity data unrealized. Knowledge of the circadian aspects of physical activity may be particularly important in lower-activity populations who engage in little to no moderate-to-vigorous activity and may illuminate novel intervention opportunities (Liu et al., 2022).

Morning Lark or night owl? Physical activity and its circadian aspects

This thesis' results contribute to current advances in the assessment of how and when physical activity is accumulated throughout the day to deepen the understanding of how movement and health are linked (Liu et al., 2022; Walker et al., 2021).

Previous epidemiological studies have investigated age-related changes in the daytime of peak physical activity based on activity counts derived from wrist-worn accelerometry (Davis

& Fox, 2007; Davis et al., 2011; Doherty et al., 2017; Sartini et al., 2015; Schrack et al., 2014; Wennman et al., 2019). The results indicated more pronounced declines in physical activity in the afternoon than in the morning with higher ages. As an individual's chronotype is an important factor underlying the diurnal timing of physical activity, the results fit well with findings from chronobiology research linking aging to a phase shift in the sleep–wake cycle toward the early morning hours (Michel et al., 2015), resulting in a higher frequency of morning types (e.g., morning larks) in the older population. As the shortcomings of physical activity assessments based on activity counts in older adults are the key message from **Chapter 2**, in the subsequent studies reported in **Chapters 3** and **4**, a novel approach was employed to assess the timing of peak physical activity based on mobility-related behavior. The comparison of the timing of peak gait activity among self-reported chronotypes revealed diurnal differences, suggesting a diurnal correspondence of mobility-related behavior and the subjectively preferred time-of-day (Fleiner & Trumpf et al., 2021).

Knowledge on an individual's habitual timing of peak mobility-related behavior could be used to personalize physical activity advice and interventions. Particularly in physically inactive older adults, the consideration of individual time preferences when designing interventions may help to increase motivation and compliance with physical activity interventions (Chaudhari et al., 2022; Cohen-Mansfield et al., 2004). Furthermore, recent evidence suggests that the timing of physical activity in older adults is linked to certain health outcomes, including metabolic health (Albalak et al., 2021), frailty (Huisingh-Scheetz et al., 2018), and cognitive impairment (Musiek et al., 2018). In these studies, higher levels of physical activity during the morning hours were associated with improved metabolic health (Albalak et al., 2021) and non-frailty status (Huisingh-Scheetz et al., 2018), while high levels of nocturnal physical activity were associated with poor metabolic health (Albalak et al., 2021). Within this context, monitoring of the circadian aspects of physical activity and its diurnal changes could potentially be used to detect deteriorations in health status, and considering the time of day when planning exercise interventions might help achieving maximal health benefits. Though research on the temporal aspects of physical activity is in its infancy, the existing evidence, including this thesis' results, indicate the potential of such an assessment approach to provide more sensitive information about health and functional status, than traditional total physical activity scores may offer.

This is especially relevant for populations, that are particularly inactive or show deviations in their circadian behavior.

The role of circadian aspects in acute dementia care

This thesis' results regarding the circadian aspects of mobility-related behavior in acute dementia (Trumpf, Haussermann, et al., 2023) reveal important and relevant information for clinicians and clinical routines. An assessment of the circadian aspects of mobility-related behavior is of particular interest in acute dementia care, as patients are often admitted due to an exacerbation of behavioral and/or psychological symptoms (BPSD), including those relating to disruptions in the circadian rest–activity cycle. The treatment of these symptoms is a central challenge in acute dementia care. However, in routine clinical practice, patients' motor behaviors are observed and reported by the nursing staff without systematic protocols and without specific information such as the time of occurrence, severity, and symptom type. Particularly during the afternoon and night, when staff-to-patient ratios are often lower than in the morning, mobility-related behavior symptoms are susceptible to being overlooked and underreported (Trumpf, Haussermann, et al., 2023; Yamakawa et al., 2012). This is problematic, as the initiation and evaluation of pharmacological and non-pharmacological treatments commonly rely on the nursing staff's documentation. Yamakawa et al. (2012) suggested that the implementation of educational interventions to improve the assessment and documentation of patients' mobility-related behavior may enable more informed treatment decisions by clinicians. However, such educational training is usually time- and labor-intensive, and even extensive documentation may not capture all activity-related information, such as activity quantity and intensity. Motion sensor-based assessments and analysis, as presented in **Chapter 4**, represent a clinically applicable method of providing clinicians with objective data regarding the circadian aspects of mobility-related behavior, including nocturnal step count, that could potentially be used to tailor treatment and evaluate interventions in acute dementia care.

The results of **Chapter 4** additionally reveal important information that may support the reconsideration of the common temporal organization of routines in acute dementia care settings. Typically, routines in acute care settings center around the morning hours, when medical ward rounds, nursing interventions, consultancy services, and non-pharmacological therapies are conducted. As a result, routines are most likely to overlap in the morning, while fewer medical, nursing, and non-pharmacological interventions are scheduled in the afternoon and evening. The focus of multiple aspects of care on the morning hours contradicts the recommendations of previous research (Baldacchino et al., 2018; Fleiner et al., 2017) and national guidelines to provide patients with dementia with structured routines through day-structuring activities (Deutsche Gesellschaft für Psychiatrie und Psychotherapie & Deutsche Gesellschaft für Neurologie, 2016).

Structured physical activity is known to have a stabilizing effect on the circadian rest–activity cycles of older adults and patients with dementia. Scheduling multiple exercise sessions during the day has been identified as a promising non-pharmacological approach to treating patients with circadian rhythm-related disorders (Baldacchino et al., 2018; Fleiner et al., 2017; Rimmer & Smith, 2009), as multiple exercise sessions can stimulate patients' activity state during the day by limiting excessive inactive time (Rimmer & Smith, 2009), which has been linked to the development of BPSD (Fleiner et al., 2015; Scherder et al., 2010). Patients with sundowning syndrome may particularly benefit from exercise sessions scheduled during the second half of the day (Venturelli et al., 2016).

The implications of an objective assessment of patients' mobility-related activity and its circadian aspects as well as the temporal organization of physical activation in routine care and its expected effects on circadian rhythm-related disorders of motor behavior are extremely relevant to acute dementia care. The implementation of appropriate assessments could lead to the improved identification of patients with specific disruptions in circadian motor behavior (e.g., sundowning syndrome), enhancing clinicians' ability to provide informed and tailored treatment.

Time to go beyond total scores of physical activity?!

Although total scores of physical activity and sedentary behavior are clinically important for a quick assessment of a person's physical activity level and functional status, they reduce the rich data collected by motion-sensor based monitoring of physical activity and sedentary behavior (F. Liu et al., 2021). Methods for quantifying the circadian aspects of mobility-related behavior, such as active period analysis, may be utilized to identify differences in peak mobility-related behavior in community-dwelling older adults and in populations at high risk for circadian rhythm-related disorders, such as patients with dementia (Fleiner & Trumpf et al., 2021; Trumpf, Haussermann, et al., 2023). Although such approaches go beyond the traditional assessment of intensity-based total physical activity scores and may be useful for tailoring interventions, they only can only provide partial information regarding how physical activity and sedentary behavior are accumulated throughout the day. For example, one individual may routinely achieve 20–30 minutes of walking per day accumulated predominantly through a single bout of prolonged activity within the active period, while another may engage in multiple short active bouts throughout the day. Although both individuals accrue similar amounts of active and sedentary time, their number of transitions between active and sedentary states, or degree of activity fragmentation, differs considerably. Preliminary research in this area has indicated that a higher degree of activity fragmentation, meaning a shorter average duration of activity bouts with a higher frequency of transitioning from activities of any intensity to a sedentary state, is associated with higher age and negative health outcomes (Di et al., 2017; Schrack et al., 2019; Wanigatunga et al., 2018). Inversely, a higher degree of sedentary behavior fragmentation appears to be favorable, as prolonged sedentary bouts are associated with negative health outcomes. Although longer activity bout durations seem to be associated with a better functional status, adding short bouts of physical activity of any intensity might limit sedentary behavior and therefore have health benefits.

Thus far, accumulation patterns of physical activity and sedentary behavior have primarily been investigated using activity count or raw acceleration data derived from wrist-worn accelerometers. As highlighted in this thesis, wrist-worn actigraphy and analysis based on activity counts do not enable a detailed assessment of sedentary behavior. Because hybrid motion sensors can assess body postures and postural changes, they enable a direct measurement of transitions between active and sedentary bouts, such as when transitioning from standing to sitting. Initial approaches examined patterns of physical activity and sedentary behavior based on activity types and postural transitions (Ghosh et al., 2018; Healy et al., 2013). The average number of sit-to-stand transitions per hour has been proposed as a measure of the transitions between sedentary and active bouts (Healy et al., 2013). From the perspective of clinical applicability, sit-to-stand transitions are easy to understand and have already been used as a target parameter in interventions with younger adults (Healy et al., 2013). Ghosh et al. (2018) developed an approach to calculate the probability with which an individual engages in a certain state (e.g., activity type, posture or postural transitions) as well as the probability to change between states using machine learning techniques. In their proof-of-concept study, they have shown that the transitions between states capture the rich dynamical structure of mobility-related behavior.

The assessment of accumulation patterns based on clinically applicable metrics such as transitions between activity types and postures may offer a more sensitive measure of changes in physical activity and sedentary behavior in older adults, than total scores of physical activity and sedentary behavior, enabling the exploration of more creative physical activity promotion methods, which could particularly benefit older adults.

One-size-fits-all vs. personalized physical activity interventions

Current strategies for exercise and physical activity at a population level predominantly aim to increase moderate-to-vigorous physical activity to meet global physical activity recommendations. This one-size-fits-all approach often fails to achieve meaningful physiological and health benefits (Jones et al., 2021). Older adults whose chronic conditions prevent them from meeting general activity recommendations could particularly benefit from personalized physical activity advice and interventions. This thesis identified motion sensor-based physical activity monitoring as an innovative and clinically applicable approach to providing individualized physical activity interventions in older adults (Trumpf, Schulte, et al., 2023). The ability to gather body-worn, motion sensor-derived physical activity data assessed in real-life conditions enables the performance of a targeted needs analysis and the subsequent derivation of tailored physical activity interventions. Additionally, the use of motion sensors for continuous self-monitoring and the provision of direct feedback throughout interventions promises enhanced control of the intervention. The direct feedback from motion sensors in combination with the setting of personalized goals, such as increasing steps or reducing sitting time per day, empowers older adults to monitor and control their physical activity behavior. To date, however, the potential of motion sensor-based data to guide physical activity interventions has not been fully realized (Trumpf, Schulte, et al., 2023). As highlighted in **chapter 5**, existing intervention approaches based on motion sensor data in older adults primarily focus on improving the amount of daily physical activity by targeting daily step count (Larsen et al., 2019; Oliveira et al., 2019; Trumpf, Schulte, et al., 2023). Personalization in these approaches is achieved by setting daily step goals based on the individual's baseline measurements (Trumpf, Schulte, et al., 2023). Advancements in wearable motion sensor technology have enabled the monitoring and provision of direct feedback regarding additional aspects of physical and particularly sedentary activities, which could be valuable in interventions targeting sedentary behaviors. However, few such approaches have thus far been established. The systematic review presented in this thesis identified only one trial that aimed to reduce daily sedentary time (Rosenberg et al., 2020). Rosenberg et al. (2020) used a wrist-worn motion sensor that provided gentle vibrations every 15 minutes to cue breaks from sitting throughout the day in obese geriatric patients, which led to a reduction in sitting time of 58 minutes per day in the intervention group compared to the control group. This represents a personalized intervention aiming to reduce potentially harmful behavior patterns when they occur, which differs from the majority of personalized interventions in the literature that promote an increase in physical activity and thus solely target the achievement of a certain amount of physical activity. Physical activity monitoring using wearable motion sensor technology offers greater potential to personalize interventions than is currently being employed in existing approaches that are limited to total step count-based physical activity goals. As previously stated, focusing on individuals' chronotype to improve compliance, promoting physical activity at specific times of the day, improving accumulation patterns of physical activity and sedentary behavior, and utilizing physical activity interventions to structure the daily routines of patients with dementia represent approaches that utilize the high-frequency time-series data assessed with wearable physical activity monitoring technology to enhance the individualization of physical activity interventions.

The ultimate goal of physical activity interventions should be the adoption of a physically active lifestyle. Achieving this goal in the predominantly inactive population of older adults can only be accomplished by stimulating behavioral changes. Individually tailored interventions using motion sensor-based physical activity monitoring may facilitate behavioral change by reducing barriers through the consideration of individual capabilities, preferences, and needs.

Methodological considerations and critical reflections

This thesis has methodological strengths and weaknesses that should be taken into consideration when interpreting its findings. The thesis' major strength is that it clearly demonstrates the advantage of functional mobility-based assessments of physical activity using hybrid motion sensor systems over actigraphic approaches in older adults and specifically in geriatric patients. Mobility-related assessments of physical activity can provide clinically applicable outcomes of overall physical activity and sedentary behavior in older adults, as they facilitate evidence-based decision-making and are highly relevant to the target population. Furthermore, mobility-related assessments of physical activity enable the analysis of specific aspects of mobility in daily life, including the temporal distribution of physical activity. Several limitations in the generalizability of this thesis' results, particularly those presented in **Chapters 3** and **4**, must be noted. First, the results are limited to samples of healthy and relatively active community-dwelling older adults and patients with dementia in a highly specific acute care setting. It is thus uncertain whether the results can be applied to older individuals with severe mobility impairments or other mental disorders. Though the results presented in **Chapter 4** reveal important aspects of organizational routines employed in the acute dementia care setting, these routines (e.g., mealtimes, therapy schedules, wake-up times, bedtimes) may have biased the timing of patients' physical activity. The generalization and transfer of the results to patients in other dementia care settings thus remains unclear. Second, even within the included samples, the generalizability of the results of the circadian aspects of physical activity needs to be critically considered, as the analyses do not fully address day-to-day variance. In the analysis presented in **Chapter 3**, the time of day of peak gait activity was averaged over several days, thus inter-daily variations in the timing of the active period may have been overlooked. The subsequent analysis in **Chapter 4** attempted to address intraindividual day-to-day variations by comparing the timing of peak gait activity between two measurement days and assigning these active periods to corresponding categories (start of both active periods during the morning or afternoon). Although the results suggest consistency in the timing of physical activity behavior, further investigations addressing day-to-day variations. Hence, the reliability of the circadian aspects of mobility-related behavior is still uncertain.

Nevertheless, this thesis presented a simple approach to objectifying a temporal aspect of daily physical activity distribution and yielded data regarding the timing of peak gait activity that is easy to interpret, promising high practical feasibility. However, the exploratory studies in **Chapters 3** and **4** only presented initial results. The active period analysis method's discriminative ability to assess the temporal aspects of mobility-related behavior to identify disruptions in circadian motor behavior and sensitivity to change when evaluating treatment effects remains unclear. To fully determine the clinical applicability of assessing the circadian aspects of mobility-related behavior, further in-depth studies analyzing this assessment method's clinical relevance, including its clinical validity, and evaluating different older adult populations and settings are needed.

Physical activity as a vital sign in geriatric health care

Considering the diverse health benefits of a physically active lifestyle, physical activity and sedentary behavior should be given special emphasis in geriatric health care. Body-worn motion sensor technology can provide clinically applicable physical activity data, which may facilitate the adoption of physical activity and sedentary behavior as multidisciplinary and cross-sectoral responsibilities.

When admitted to a hospital, patients have a high risk of experiencing prolonged sedentary periods (Fleiner et al., 2016), even when they had an active lifestyle before admission (Harvey et al., 2018). Physical inactivity can lead to a deterioration in patients' medical condition independent of the admission indication. The continuous monitoring of physical activity as an integral component of each hospital stay and the initiation of appropriate intervention measures may prevent the detrimental consequences of prolonged sedentary behavior. To achieve these benefits, a multidisciplinary awareness of patients' physical activity is crucial. Interfacing physical activity data with hospital information systems and digital patient files and reviewing physical activity data during multidisciplinary team meetings and medical rounds constitute important stepping stones for this purpose. Creating an environment that values the health benefits of appropriate physical activity may raise patients' awareness of their physical activity behavior. However, such an approach relies on clinically applicable assessment strategies, including intuitive and actionable metrics as well as measurement tools that are cost-effective, easy to utilize, and accepted by patients and health care workers. The hospital stay presents an opportunity to provide patients with personalized physical activity interventions that can be continued after discharge. The above-mentioned strategies for integrating physical activity data into digital patient files and improving patient awareness regarding their physical activity will inform aftercare institutions and simplify cross-sectoral treatments.

The inclusion of motion sensors (i.e., inertial measurement units) in wearable devices and smartphones has already contributed to a user-friendly and low-threshold integration of motion sensing technology into the daily life of large portions of society. The number of global smartphone users is estimated to be approximately 6.6 billion, indicating that more than 80% of the world's population owns a smartphone. The ubiquity, accessibility, and high acceptability of smartphones, wearables, and applications combined with easy-to-use interfaces, automatic data processing and analysis possibilities, and real-time reporting of physical activity offer tremendous potential for monitoring and intervening in physical activity and sedentary behaviors, similar to the widespread and accessible manner in which vital signs such as heart rate and blood pressure are tracked. During the COVID-19 pandemic, telemedicine approaches to delivering health care services gained importance. As the assessment and transmission of physical activity data obtained with wearables and smartphones do not require face-to-face interaction, this method may have particular value for telemedicine consultations. General physical activity levels, including sedentary behavior, and their evolution over time can indicate a change in health state and the necessity of further clarification measures, such as a more detailed analysis of physical activity behavior. The integration of motion sensing technology into smartphones and wearables allows patients to self-monitor their physical activity behavior and facilitates successful interventions.

Implications for future research

This thesis results, alongside previous findings, highlight that assessment approaches of physical activity in older adults should encompass low activity intensities, body postures and mobility-related activities in order to get full insight into older adult's real-life physical activity. This thesis further showed that frequently used instruments for measuring physical activity in older adults (e.g., questionnaires, actigraphs) are not suitable for assessing physical activity in such nuanced manner.

The development of a framework similar to the SBRN's consensus project that comprises an extension of the energy-focused definition of physical activity by considering body postures might provide more nuanced activity classifications, especially at the bottom end of the basic energy-based classification of physical activity which probably reflect the physical activity of older adults more adequately. The widespread adoption of such a framework might enable consistently focused research on physical activity in older adults by facilitating the use of appropriate instruments for the assessment of physical activity and sedentary behavior and thus may provide a more profound understanding of the association of physical activity and health in older adults.

Current body-worn motion sensors and their corresponding algorithms that assess body posture, postural transitions, and activity types appear to be most suitable for assessing physical activity in older adults. A challenge concerning their use to study the effects of physical activity on health and health care arises from the plethora of research- and consumer-grade devices and algorithms available that vary considerably in their accuracy. Differences in the algorithms used to process raw data, the calculation of physical activity parameters, and the placement of the device (e.g., hip, wrist, ankle, trunk) complicate the comparability of studies employing different devices to assess physical activity in older adults. Particularly in consumer-grade devices, psychometric properties are often not available or verifiable. The development of uniformly applicable algorithms that are usable independent of the device and specific health condition could enhance the understanding of the health-promoting effects of functional physical activity on older adults through enhanced comparability between individual studies. The application of such validated algorithms in consumer-grade body-worn motion sensors would constitute an important step toward the systematic integration of physical activity data into health care systems.

In addition to previous findings, this thesis highlights the relevance of research on the circadian aspects of physical activity in older adults, particularly in geriatric healthcare. While previous research has primarily investigated the circadian aspects of physical activity within its intensity-based dimension, this thesis presented an approach that focuses on mobility-related activity.

Although the results suggest that the approach presented allows objectification of a temporal aspect of physical activity and provides data that appear practicably applicable, its clinical validity remains to be established. To be useful in clinical settings, the presented approach should be able to detect patients with impaired circadian motor behavior and should be able to detect changes over time to evaluate treatment effects. Future research should investigate whether the presented approach is suitable for this purpose.

Chapter 7

Conclusion

The findings of this thesis reveal important and valuable information regarding physical activity assessment and intervention approaches using motion sensor-based monitoring in older adults and geriatric health care settings. An assessment of real-life physical activity should encompass all activity intensities (light, moderate, vigorous) as well as mobility-related behavior and sedentary behavior, in order to obtain a comprehensive picture of an older person’s physical activity level. Motion sensors that allow to measure activity types, body postures and postural transitions (e.g., hybrid motion sensors) continuously are necessary for an assessment approach of this type. In addition to providing clinically applicable physical activity outcomes, the mobility-related assessment of physical activity can enable the analysis of specific aspects, including the temporal distribution of physical activity in daily life. Alongside previous results, this thesis highlights the relevance of assessment approaches beyond the traditional total physical activity scores, that are possibly limited especially in older adults. Being able to analyze circadian aspects of physical activity has extra relevance in geriatric health care. Finally, this thesis identified motion-sensor based physical activity monitoring as a promising approach to personalizing physical activity interventions in geriatric patients and provides valuable guidance for future studies and reviews examining the effectiveness of interventions in older adults using motion sensor-based physical activity monitoring.

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List of publications

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