JYU DISSERTATIONS 443

Lotta Palmberg

Associations of Sleep Characteristics and Fatigue with Physical Activity Patterns and Unmet Physical Activity Need in Old Age

UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF SPORT AND
HEALTH SCIENCES

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Esitetään Jyväskylän yliopiston liikuntatieteellisen tiedekunnan suostumuksella
julkisesti tarkastettavaksi yliopiston vanhassa juhlasalissa S212
lokakuun 29. päivänä 2021 kello 12.

Academic dissertation to be publicly discussed, by permission of
the Faculty of Sport and Health Sciences of the University of Jyväskylä,
in building Seminarium, Old Festival Hall S212, on October 29, 2021, at 12 o'clock.

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2021

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ISBN 978-951-39-8886-9 (PDF)
URN:ISBN:978-951-39-8886-9
ISSN 2489-9003

Permanent link to this publication: http://urn.fi/URN:ISBN:978-951-39-8886-9

ABSTRACT

Palmberg, Lotta
Associations of sleep characteristics and fatigue with physical activity patterns and unmet physical activity need in old age
Jyväskylä: University of Jyväskylä, 2021, 92 p.
(JYU Dissertations
ISSN 2489-9003; 443)
ISBN 978-951-39-8886-9 (PDF)

Many older people are unwillingly excluded from physical activity, a situation termed unmet physical activity need. Poor sleep and fatigue can hinder opportunities for physical activity and potentially lead to unmet physical activity need. To alleviate fatigue, older people adopt adaptive behaviors that may manifest as a more fragmented physical activity. This dissertation had three aims: first, to study whether fragmented physical activity patterns are associated with poorer sleep-related characteristics and higher fatigability; second, to study whether higher fatigue and poorer sleep characteristics are associated with unmet physical activity need in old age; and third, to study whether lower physical activity and fatigue precede the development of unmet physical activity need.

Data were drawn from three larger studies: the Life-Space Mobility in Old Age study (n=848), the Finnish Twin Study on Aging (n=344), and the Active Ageing – Resilience and External Support as Modifiers of the Disablement Outcome study (n=1 021), which included a subsample (n=485) participating in physical activity monitoring. The data were based on self-reports, laboratory assessments, and physical activity monitoring. The participants in the studies were aged 75 to 93 and community-dwelling.

The results showed that more fragmented physical activity patterns were associated with higher physical fatigability and poorer sleep-related characteristics. Short sleep duration and higher physical fatigability had cross-sectional associations with unmet physical activity need. Higher fatigue and unmet physical activity need showed a reciprocal association, which was explained by poorer health, and lower physical activity levels. Finally, lower physical activity level predicted the development of unmet physical activity need.

Assessment of physical activity fragmentation may be important in identifying those at risk for poorer sleep and higher physical fatigability. While poorer sleep and higher fatigue may limit opportunities for physical activity participation in old age, the will to be more physically active remains. The aging-related decline in physical activity is often unwanted, and hence many older people may need support in physical activity participation. The findings lay grounds for physical activity promotion among older people.

Keywords: activity fragmentation, physical activity participation, fatigue

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Palmberg, Lotta
Unta kuvaavien tekijöiden ja väsymyksen yhteys fyysiseen aktiivisuuden kertymiseen ja tyydyttämättömään liikunnantarpeeseen vanhuusiässä
Jyväskylä: Jyväskylä yliopisto, 2021, 92 s.
(JYU Dissertations
ISSN 2489-9003; 443)
ISBN 978-951-39-8886-9 (PDF)

Monilla ikääntyneillä ei ole mahdollisuutta lisätä fyysistä aktiivisuutta, vaikka niin toivoisivat, eli he kokevat tyydyttämätöntä liikunnantarvetta. Heikompi uni ja väsymys voivat heikentää mahdollisuuksia fyysiseen aktiivisuuteen ja johtaa tyydyttämättömään liikunnantarpeeseen. Alkaessaan väsyä ikääntyneet ihmiset muokkaavat käyttäytymistään ja päivittäinen fyysinen aktiivisuus saattaa kertyä katkonaisemmin. Tällä väitöstutkimuksella oli kolme tavoitetta: 1) tutkia onko katkonaisempi fyysinen aktiivisuus yhteydessä korkeampaan väsyvyyteen ja heikompiin unta kuvaaviin tekijöihin, 2) tutkia, ovatko korkeampi väsymys ja heikompi uni yhteydessä tyydyttämättömään liikunnantarpeeseen, ja 3) ennustavatko alempi fyysisen aktiivisuuden taso ja väsymys tyydyttämättömän liikunnantarpeen kehittymistä.

Tutkimuksessa hyödynnettiin kolmen isomman tutkimuksen aineistoa: Iäkkäiden ihmisten liikkumiskyky ja elinpiiri (n=848) -aineistoa, Finnish Twin Study on Aging (FITSA, n=344) -aineistoa ja Aktiivinen vanhuus (n=1021) –aineistoa, jonka osallistujat pitivät kiihtyvyysanturia (n=485). Muuttujat olivat itseraportoituja, laboratoriotestejä sekä kiihtyvyysanturimittaukseen perustuvia. Tutkittavat olivat kotona asuvia 75-93-vuotiaita henkilöitä.

Tulokset osoittivat, että katkonaisempi fyysinen aktiivisuus oli yhteydessä suurempaan fyysiseen väsyvyyteen ja heikompiin yöllistä lepoa kuvaaviin tekijöihin. Lyhyt unen kesto ja suurempi fyysinen väsyvyys olivat yhteydessä tyydyttämättömään liikunnantarpeeseen. Väsymyksen ja tyydyttämättömän liikunnantarpeen yhteys oli kaksisuuntainen ja selittyi heikommalla terveydellä ja matalammalla fyysisellä aktiivisuudella. Matalampi fyysinen aktiivisuus ennusti tyydyttämättömän liikunnantarpeen kehittymistä.

Fyysisen aktiivisuuden katkonaisuuden tutkiminen saattaa auttaa niiden henkilöiden tunnistamisessa, joilla on riski suurempaan fyysiseen väsyvyyteen ja heikompaan yölliseen lepoon. Heikompi uni ja väsymys voivat heikentää mahdollisuuksia fyysiseen aktiivisuuteen, mutta halu liikkua säilyy. Iän myötä vähenevä fyysinen aktiivisuus ei usein ole toivottua, ja monet ikääntyneet henkilöt saattavat tarvita erityistä tukea voidakseen lisätä fyysistä aktiivisuutta. Tulokset luovat pohjaa fyysisen aktiivisuuden edistämiselle ikääntyneillä henkilöillä.

Asiasanat: aktiivisuuden katkonaisuus, fyysinen aktiivisuus, väsymys

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ACKNOWLEDGEMENTS

This study was carried out at the Gerontology Research Center and the Faculty of Sport and Health Sciences in the University of Jyväskylä, Finland. First, I would like to express my sincere gratitude to all of the participants of the Finnish Twin Study on Aging, Life-Space Mobility in Old Age and Active Ageing – Resilience and External Support as Modifiers of the Disablement Outcome studies. Without you, this research would not have been possible. Furthermore, I would like to thank Professor Ari Heinonen, the Dean of the Faculty of Sport and Health Sciences and the Research Director Katja Kokko at the Gerontology Research Center for providing me the opportunity to conduct this research in the supportive and multidisciplinary working environment.

My deepest gratitude goes to my supervisors, Professor Taina Rantanen and Principal Researcher Merja Rantakokko, who have guided me through this journey. Thank you so much for giving your time to help me whenever I was at a crossroads and did not know how to continue. Taina, I have been privileged to have you as my supervisor since I was writing my master's thesis. Your profound expertise and achievements in research are truly inspiring. Thank you for the valuable advice you have given me during these years, and the support to trust in my own opinions. Merja, thank you for giving me the opportunity to work in your project and for your invaluable guidance through the first years of my doctoral studies. I am sincerely grateful that you always had your door open for my questions, even the smallest ones. You have a really optimistic and encouraging way of supervising and after our talks I always felt like I knew what to do.

I would also like to thank the official reviewers of this dissertation, Research Professor Timo Partonen and Associate Professor Annemarie Koster for taking the time to review this work and for your valuable comments and advice. I would like to thank Research Director Harri Sievänen for agreeing to be the opponent in the public defense of my thesis. I am grateful to the member of my steering group, Research Director Tuija Tammelin, for giving your valuable time to participate in our steering group meetings. Furthermore, I thank Michael Freeman for the language editing and to Anne Viljanen, PhD, for the scientific editing of this dissertation.

I would like to express my gratitude to all my co-authors for your insightful comments and contribution in the original papers presented in this thesis. Furthermore, I would also like to thank all the co-workers, past and present, at the Gerontology Research Center, with special thanks to the members of the AGNES and the Equal-Part research groups. I have been very privileged to work with such a wonderful group of people. Furthermore, I am grateful to all my fellow doctoral students at the Gerontology Research Center for your peer support and sharing our doctoral journeys over these years. I would like to thank Senior Researcher Timo Rantalainen for all the valuable help you have given me with the accelerometer data and for giving me an opportunity to continue research in your project. A warm thank you goes to Postdoctoral Researchers Sini

Siltanen and Anu Tourunen for your friendship and support during these years. Furthermore, I would like to thank my fellow Doctoral Students Heidi Leppä and Kaisa Koivunen especially for sharing the final steps of our doctoral journeys together and for our Monday afternoon peer support meetings.

Finally, I would like to express my warmest gratitude to my family, friends and relatives for their support and for being in my life and bringing so much joy into my life outside work. A special thanks goes to my parents, Timo and Arja, thank you for the unconditional and endless support that I have received from you throughout my life. I have always been able to rely on your help. My sister Riikka, thank you for your support and for always being in my life. Juuso, thank you for your patience on all those long days that you spent taking care of our baby while I was writing this dissertation. I am thankful for you being in my life. Finally, my dear daughter Hilda, thank you for bringing so much joy into my life. I am deeply grateful to be your mother.

Jyväskylä 16.9.2021
Lotta Palmberg

FIGURES

TABLES

LIST OF ORIGINAL PUBLICATIONS

The dissertation is based on four original publications (Studies II, III, IV and V) and one comment letter (Study I), and also includes unpublished data.

I Palmberg, L., Portegijs, E., Karavirta, L., & Rantanen, T. (2021). Comment on "Fatigability: A prognostic indicator of phenotypic aging". The Journals of Gerontology Series A: Biological Sciences and Medical Sciences 76 (8), e159-e160.

II Palmberg, L., Rantalainen, T., Rantakokko, M., Karavirta, L., Myllyntausta, S. Leppä, H., Portegijs, E. & Rantanen, T. Activity fragmentation, physical activity and patterns of nighttime rest among community-dwelling older people. Submitted for publication.

III Palmberg, L., Rantalainen, T., Rantakokko, M., Karavirta, L., Siltanen, S., Skantz, H., Saajanaho, M., Portegijs, E. & Rantanen, T. (2020). The associations of activity fragmentation with physical and mental fatigability among community-dwelling 75-, 80-, and 85-year-old people. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences 75 (9), e103-e110.

IV Palmberg, L., Viljanen, A., Rantanen, T., Kaprio, J., & Rantakokko, M. (2020). The Relationship between Sleep Characteristics and Unmet Physical Activity Need in Older Women. Journal of Aging and Health 32 (3-4), 199-207.

V Palmberg, L., Portegijs, E., Rantanen, T., Aartolahti, E., Viljanen, A., Hirvensalo, M., & Rantakokko, M. (2019). Neighborhood Mobility and Unmet Physical Activity Need in Old Age: A 2-Year Follow-Up. Journal of Aging and Physical Activity 28 (3), 442-447.

As the first author of the original publications, considering the comments from the co-authors, my responsibility has been drafting, prepared the data for statistical analyses, performed statistical analyses, and taken the main responsibility of writing the manuscripts. I have actively participated in the data collection in the Active Ageing (AGNES) -study, of which data were used in Studies I, II and III. In Studies IV and V I was priviledged to use pre-existing data.

ABBREVIATIONS

AGNES	Active Aging – Resilience and External Support as Modifiers of the Disablement Outcome
ANOVA	One-way analysis of variance
ASTP	Active-to-Sedentary Transition Probability
CES-D	Center for Epidemiologic Studies Depression Scale
CI	Confidence interval
FITSA	Finnish Twin Study on Aging
LISPE	Life-Space Mobility in Old Age
MAD	Mean Amplitude Deviation
MET	Metabolic equivalent
MFS	Mental Fatigue Subscale
MI	Multiple imputation
MMSE	Mini Mental State Examination
OR	Odds Ratio
P	P-value
PEF	Perceived exertion fatigability
PFS	Physical Fatigue Subscale
PSG	Polysomnography
RMR	Resting metabolic rate
RPE	Borg Rating of Perceived Exertion
SCN	Suprachiasmatic nucleus
SD	Standard deviation
SE	Standard error
SFS	Situational Fatigue Scale
SPPB	Short Physical Performance Battery
SRI	Sleep Regularity Index
TECM	Theory of Energetic Cost Minimization
TIB	Time in bed
YPAS	Yale Physical Activity Survey
WHO	World Health Organization
6MWT	6-minute walk test

CONTENTS

1 INTRODUCTION

Physical activity can be considered one of the basic human needs (World Health Organization 2007). Physical activity has been defined as any movement that results in an increase in energy expenditure (Caspersen, Powell & Christenson 1985). Physical activity in its various forms is an important part of everyday life. For instance, it can function as a form of transportation to access the surrounding community, facilities, and enable participation in valued activities. Physical activity has also been widely recognized for its important role in maintaining health and physical function (Warburton, Nicol & Bredin 2006; Paterson & Warburton 2010). On the other hand, the adverse consequences of inactivity on health have been widely recognized. This is important as a rather large proportion of older people are excluded from physical activity against their will. Unmet physical activity need is a phenomenon that describes a disparity between the willingness and perceived opportunity for physical activity and can therefore indicate inequity in physical activity (Rantakokko et al. 2010). The concept of unmet physical activity need emphasizes the subjective perception of inadequate physical activity, rather than the objective absolute amount of physical activity or the reasons behind inadequate opportunities for physical activity participation. However, previous studies show that poor health, mobility limitations, environmental barriers and lower physical activity levels are all associated with unmet physical activity need (Rantakokko et al. 2010; Eronen et al. 2012). These earlier findings indicate that decreased individual capabilities can render older people more vulnerable to exclusion from physical activity participation. Despite these findings, the determinants of unmet physical activity need remain largely unstudied.

Sleep is vital for health and wellbeing. With advancing age, sleep changes in several ways (Ohayon et al. 2004) and, owing to the aging-related increase in chronic conditions, the prevalence of sleep disturbances also increases (Ancoli-Israel 2009). Research has shown that physical activity is beneficial for various aspects of sleep (Kredlow et al. 2015; Vanderlinden, Boen & van Uffelen 2020). Other studies have shown that insufficient and poor quality sleep also lead to reduced physical activity levels (Lambiase et al. 2013; Holfeld & Ruthig 2014;

Gabriel et al. 2017), supporting a bidirectional association between physical activity and sleep. One of the consequences of poor and insufficient sleep is fatigue (Hossain et al. 2005; Goldman et al. 2008). Sleep-related fatigue may be one of the factors explaining why poor sleep leads to lower physical activity levels (Gilbert et al. 2018).

Fatigue is not only a consequence of sleep disturbances, but is a multifactorial symptom related to several diseases and also has idiopathic forms (Avlund 2010). It is also one of the indicators of frailty and can identify those at higher risk for the onset of frailty several years beforehand (Stenholm et al. 2019). Fatigue is rather common in old age and has a debilitating effect on participation in physical activity and other valued activities. In an attempt to alleviate and cope with fatigue, older people adopt different adaptive behaviors such as taking breaks, slowing down and reducing their physical activities to maintain fatigue at an acceptable level (Eldadah 2010; Schrack, Simonsick & Ferrucci 2010; Kratz et al. 2019). These strategies may help older people maintain their engagement in activities (Skantz et al. 2019), but they can also accelerate functional decline (Fried et al. 2000, Mänty et al. 2007). Moreover, these strategies to alleviate fatigue may also make the recognition of fatigue more difficult. Fatigability is a phenotype of fatigue, which anchors fatigue to different activities standardized by duration and intensity (Eldadah 2010). When fatigue is anchored to daily activities, the proportion of people suffering from fatigue increases steeply with age (Avlund 2010). Early signs of increasing fatigability can potentially be seen in the shortening of physical activity bouts, resulting in a more fragmented accumulation of activity, as shown by continuous physical activity monitoring (Schrack et al. 2019). It has been suggested that fragmented physical activity accumulation is an early sign of accelerated aging (Wanigatunga, Ferrucci & Schrack 2019).

Fatigue has often been defined as subjective feeling of low energy, and it has been suggested that the mechanism underlying fatigue could be related to energy regulation (Alexander et al. 2010; Eldadah 2010). The aging-related increase in fatigue can partly be explained by the growing energetic cost of daily activities and the decrease in the total energy available for allocation to these activities (Schrack, Simonsick & Ferrucci 2010). While the function of sleep is not thoroughly understood, theories state that the primary functions of sleep are connected to energy conservation (Berger & Phillips 1988) and restoration (Adam & Oswald 1983). Thus, failing to achieve sufficient and restorative sleep could affect the energy reserve available for physical activity and increase susceptibility to fatigue. Another recent theory explaining physical activity participation states that the avoidance of physical activity may be founded on an internal tendency to conserve energy (Cheval et al. 2018, Cheval et al. 2019), which could explain why, especially given the aging-related increase in the energetic cost of physical activity, older people tend to take breaks, slow down and avoid physical activities in an attempt to conserve energy. These theories and findings may help to explain why people with poor sleep and fatigue are less able to bring themselves to participate in physical activity and perceive their opportunities for physical activity as poor. Previous studies, however, have not targeted these associations.

Hence, the aims of this dissertation were: to study whether fragmented physical activity patterns are associated with poorer sleep characteristics and higher physical and mental fatigability; to study whether higher fatigue, higher fatigability and poorer sleep characteristics are associated with unmet physical activity need in old age; and to study whether lower physical activity levels, lower neighborhood mobility and higher fatigue precede the development of unmet physical activity need over time.

2 REVIEW OF THE LITERATURE

2.1 Physical activity

2.1.1 Physical activity in old age

Physical activity can be defined as "any bodily movement produced by skeletal muscles that results in energy expenditure" (Caspersen, Powell & Christenson 1985). In comparison to planned exercise, physical activity is a wider term that embraces all movement, including household chores and daily errands. As opposed to physical activity, sedentary behavior can be defined as any waking activity performed in a sitting, reclining, or lying posture and with energy expenditure of ≤1.5 metabolic equivalents (MET) (Tremblay et al. 2017), when one MET is equivalent of the energetic cost of sitting at rest (Jetté, Sidney & Blümchen 1990). On this definition, standing behaviors cannot be considered as sedentary behavior (Tremblay et al. 2017). Physical inactivity, in turn, refers to not performing a sufficient amount of physical activity, or not meeting the relevant physical activity guidelines (Barnes et al. 2012).

Physical activity decreases with advancing age and older people tend to shift towards lighter intensity physical activities (DiPietro 2001; Schrack et al. 2013; Wennman et al. 2019). Furthermore, older people accumulate more physical activity during the earlier hours of the day (Wennman et al. 2019). Although physical activity levels often decrease with age, physical activity is reported as the most important hobby by older people (Karvinen, Koivumäki & Kalmari 2012). The most common form of physical activity among older adults is walking (Lim & Taylor 2005; Amireault, Baier & Spencer 2018), which is often performed in an outdoor environment. Other popular types of physical activity include cycling, skiing, home gymnastics, and mushroom and berry picking (Karvinen, Koivumäki & Kalmari 2012). The World Health Organization (WHO) recommends that, to maintain their health and physical function, older people should engage regularly in multicomponent physical activity, including aerobic, strength, and balance training (Bull et al. 2020). The WHO guidelines recommend engaging in at least 150-300 minutes of moderate-intensity, or 75-150 minutes of vigorous, aerobic physical activity per week, and strength training at least twice per week. Multicomponent physical activity should be performed on at least three days per week. Older people with limitations in physical function or chronic diseases should be as physically active as their functional ability allows (Bull et al. 2020). Older people are, however, less likely than younger adults to achieve the level of physical activity considered necessary for health-enhancing benefits (Bennie et al. 2017; Wennman & Borodulin 2021). Physical activity types that have been associated with a higher likelihood of reaching the physical activity guidelines among both older men and women are walking and muscle strengthening exercise (Wennman & Borodulin 2021).

2.1.2 Neighborhood mobility as an indicator of physical activity

Mobility is important for achieving adequate physical activity levels in old age. As opposed to the definition of physical activity, mobility can be defined as movement from one place to another in all its forms, either by foot or any other form of transportation (Satariano et al. 2012). Mobility is a central requirement for independent living and participation in valued activities (Rantanen 2013).

Going outdoors can be considered often a prerequisite for participation in physical activities. Many older people accumulate physical activity when participating in activities that require going outdoors, such as walking, shopping and visiting family or friends (Davis et al. 2011; Winters et al. 2015; Tsai et al. 2016). Walking is the most common form of mobility in old age and an important element of transportation to different locations in the sense that accessing public transportation or going to one's car usually requires walking at least short distances (Karvinen, Koivumäki & Kalmari 2012; Rantanen 2013). Older people's physical activity levels tend to remain rather low when they stay indoors or in the immediate vicinity of their homes but increase when they go out in their neighborhood and beyond (Portegijs et al. 2015). Out-of-home trips increase physical activity even in the case of motorized transportation (Davis et al. 2011; Portegijs et al. 2015), but especially when active transportation (i.e., walking or cycling) or public transportation (Davis et al. 2011) is used.

Although the concept of neighborhood has commonly been used in studies, its spatial boundaries are difficult to define (Guo & Bhat 2007). Neighborhood environments are, however, of especial importance for mobility in old age. Neighborhood characteristics can either facilitate or hinder older people's participation in physical activity (King et al. 2005; Li, Fisher & Brownson 2005; Portegijs et al. 2020). Especially in neighborhoods that are well suited for walking, most trips to nearby destinations are made on foot (Winters et al. 2015). Furthermore, many of a person's social networks are located in their neighborhoods (Thomése & Van Tilburg 2000), and maintaining access to neighborhood facilities may be especially important in old age (Buffel et al. 2012). Going outdoors into the neighborhood is also important for health and physical function in old age. Going outdoors daily can prevent the onset of several adverse health conditions (Jacobs et al. 2008). While going outdoors into the neighborhood at least four times per week can prevent the onset of frailty (Xue et al. 2008), going outdoors into the neighborhood at least once per week may be sufficient for the maintenance of physical function among frail older people (Shimada et al. 2010).

2.1.3 Physical activity fragmentation

Research on the health benefits of physical activity began in the 1950s, when Morris and colleagues discovered that physically active workers were less likely to die of coronary heart disease (Morris et al. 1953; Morris & Crawford 1958). Since this initial groundbreaking evidence on the health benefits of physical activity, research in the field has expanded, especially during recent decades (Varela et al. 2018). Many studies have shown that physical activity has important health benefits, also in old age. For example, higher physical activity levels have been associated with lower presence of chronic diseases, better physical function and lower risk for mortality (Pate et al. 1995; Leveille et al. 1999; Warburton, Nicol & Bredin 2006; Paterson & Warburton 2010; Yorston, Kolt & Rosenkranz 2012). In sum, physical activity can be regarded as essential for the maintenance of health and physical function in old age.

When focusing on the associations of physical activity and health, it is also meaningful to focus on how physical activity accumulates throughout the day. Not only total physical activity, but the patterns and duration of active and sedentary bouts have also been found to be associated with higher risk for adverse health outcomes and mortality (Bellettiere et al. 2017; Di et al. 2017; Diaz et al. 2017; Wanigatunga et al. 2019). While a reduction in the duration of sedentary bouts is associated with decreased risk for adverse health outcomes (Bellettiere et al. 2017; Diaz et al. 2017), the accumulation of physical activity in shorter bouts increases it (Di et al. 2017; Wanigatunga et al. 2019). Wanigatunga and colleagues (2019) found that older people who engaged more frequently in short physical activity bouts that lasted less than 5 minutes had higher risk for mortality.

Studies often using self-reports, have shown that older people may start to modify their walking by slowing down, taking breaks, or reducing walking frequency. These changes can be conscious or subconscious, and can be early signs of functional decline and preclinical disability (Fried et al. 2000; Mänty et al. 2007). However, by modifying their walking, older people may also be able to reduce environmental press on mobility and continue participation in valued activities (Rantakokko et al. 2016; Rantakokko et al. 2017; Skantz et al. 2019). Walking modifications can thus be adaptive when they allow continuing participation, or maladaptive when they lead towards avoiding participation in mobility activities (Skantz et al. 2019).

The concepts of adaptation and physical activity bouts have also been used in the context of physical activity fragmentation. Along with increasing age and accompanying health decline, it may become increasingly difficult to maintain longer bouts of activity (Schrack et al. 2019). Consequently, activity bouts may become shorter and more fragmented as, with shortening of activity bouts, transitioning from the active to sedentary state may become more frequent (Schrack et al. 2019). In recent studies, activity fragmentation has been quantified from accelerometer-based data as the Active-to-Sedentary Transition Probability (ASTP), which is calculated as the reciprocal of physical activity bout duration (Wanigatunga et al. 2018; Schrack et al. 2019). Higher scores on the ASTP indicate a higher probability of transitioning from an active to a sedentary state (Schrack et al. 2019). Higher ASTP has been associated with higher perceived physical fatigability, lower physical function (Schrack et al. 2019) and higher mortality risk among older people (Wanigatunga et al. 2019). It has been suggested that more fragmented patterns of physical activity could indicate an acceleration of the aging process (Wanigatunga, Ferrucci & Schrack 2019), and thus could be an early marker of functional decline beyond total physical activity volume. In line with this approach, the fragmentation of rest and activity cycles has also been quantified in several studies (Lim et al. 2011), where more fragmented rest-activity patterns are described as higher intra-daily variability in activity and rest.

A theoretical approach explaining how older people may stay active and participate in meaningful activities despite declining resources is the model of Selection, Optimization with Compensation (SOC), introduced by Baltes and Baltes (1990). The SOC model posits that maintaining participation in valued activities can be attained by adaptive strategies of selection, optimization, and compensation. Selection refers to older people selecting the most important goals that they want to attain, optimization refers to selecting the best means to attain the goals selected, and compensation refers to with acquiring new resources to compensate for losses (Baltes & Baltes 1990). The adaptive strategies chosen in the face of declining physical function and fatigue could include pacing and taking breaks, which is likely to be seen in accelerometer data as more fragmented accumulation of physical activity.

2.1.4 Assessment of physical activity

Physical activity can be assessed with self-report questionnaires or with accelerometers. Of these, self-reported physical activity measures are the most commonly used in studies (Sallis & Saelens 2000). Self-reported physical activity captures the intensity and frequency of physical activity, including household tasks that may not typically be regarded as physical activity. Self-reports are inexpensive and easy to administer and can also be used with larger samples. Self-reported measures, however, are prone to recall bias (Sallis & Saelens 2000, Washburn 2000), as people may not be able accurately to remember details of their engagement in different physical activities. Recall bias, especially, may be an issue in the case of lighter physical activities, which are most commonly performed in old age (Washburn 2000). Furthermore, people may overestimate their physical activity level and under estimate their sedentary time compared to accelerometer-based assessment (Dyrstad et al. 2014; Cerin et al. 2016).

Accelerometers are useful in tracking physical activity in free-living environments (Schrack, Cooper et al. 2016). The advantage of accelerometers is that they are able to assess physical activity in normal life and are also able to capture lighter activities that people may not be able to recall. Traditionally, accelerometer-based data has been reported according to intensity-based categorization. The usefulness of intensity-based categories has, however, been contested recently, among older people (Schrack et al. 2018). With increasing age and declining physical function, the relative intensity of physical activity may increase, although the intensity levels may seem lighter based on accelerometer data (Kujala et al. 2017). Studies have shown that for those with slower self-selected walking speed, the energetic cost of walking may be higher (Schrack et al. 2012, Schrack, Zipunnikov et al. 2016). Older people with poorer physical function and habitual slow walking speed may therefore not be capable of performing activities classified as vigorous based on absolute intensity. A potential alternative among older people is to study the patterns of physical activity accumulation. Accelerometers can be used to study bouts of sedentary behaviors and movement, using measures such as activity fragmentation (Wanigatunga et al. 2018; Schrack et al. 2019). Depending on their location, accelerometers can also be used to accurately assess body postures (Schrack, Cooper et al. 2016). Posture estimation, however, may be particularly useful in evaluating physical behavior among older people, as it can also be accurately measured among older people who are frail (McCullagh et al. 2016). Posture estimation is also needed to separate sedentary from standing time (Tremblay et al. 2017). In physical activity research, accelerometers have been often removed before going to bed and attached after waking up in the morning, depending on the placement location. Accelerometers, however, allow movement and non-movement behaviors to be measured on the entire 24-hour continuum (Schrack, Cooper et al. 2016).

2.2 Unmet physical activity need in old age

Inactivity is a major public health concern in the developed countries. When focusing on physical inactivity at a population level, it is important to remember that some people are inactive, not by choice but because they do not have the opportunity to increase physical activity. Moreover, when considering physical activity participation in old age, older people’s perceptions of what constitutes an adequate level of physical activity should also be taken into account.

2.2.1 Physical activity as a basic need

Physiological and psychological basic needs, in general, can be defined as “energizing states that, if satisfied, conduce toward health and wellbeing but, if not satisfied, contribute to pathology and ill-being” (Ryan & Deci 2000). Unmet needs in old age have been generally studied in relation to unmet need of health care services, unmet need of assistance in activities of daily living (Allen, Piette & Mor 2014; He et al. 2015; Zhu 2015; Andrade & Andrade 2018; Berridge & Mor 2018) or unmet needs related to housing or income (Blazer, Sachs-Ericsson & Hybels 2005; Sachs-Ericsson, Schatschneider & Blazer 2006; Blazer, Sachs-Ericsson & Hybels 2007). Physical activity can also be considered a basic need, as movement is one of the most basic human functions (World Health Organization 2007). It has been suggested that movement is so essential to humans that energy is shifted away from it only when other even more important life-preserving activities are threatened (Schrack, Simonsick & Ferrucci 2010). However, many older people are left out of physical activity despite being willing to increase it. To address this apparent disparity, the research group in which I belong to has extended the concept of physical activity as a basic need by studying unmet physical activity need among older people. Unmet physical activity need can be defined as "willingness to be more physically active while perceiving no opportunities to increase physical activity" (Rantakokko et al. 2010). It is an undesirable situation and could potentially lead to ill-being among older people. The concept of unmet physical activity need focuses on individuals' own perception of adequate physical activity and is, therefore, a different concept that the amount of physical activity that is recommended for maintaining health and physical function (Bull et al. 2020) and from the reasons behind poor opportunities for physical activity participation. In previous studies, unmet physical activity need was reported by 14% of community-dwelling participants, suggesting that it may be a rather common phenomenon among older people (Rantakokko et al. 2010; Eronen et al. 2014). Unmet physical activity need can be considered as an indicator of inequity in physical activity. The importance of equity in physical activity has also been noted for decades in policy actions that have targeted the enhancement of equity in physical activity, including among those with functional limitations (World Health Organization 2002). Besides being a basic need itself, participation in physical activity can also support the fulfillment of other basic needs (Springer, Lamborn & Pollard 2013).

The concept of unmet physical activity need posits that physical activity is a basic need for all, and the perception of unmet need for physical activity can be harmful irrespective of the individual's physical activity level. It can therefore be considered a felt need, which highlights people's own perception (Bradshaw 1972). Previously, basic needs that are not met have been shown to increase the risk for decline in physical function (Sachs-Ericsson, Schatschneider & Blazer 2006), depressive symptoms (Blazer, Sachs-Ericsson & Hybels 2007), and mortality (Blazer, Sachs-Ericsson & Hybels 2005; He et al. 2015). These, however, have been studied in the context of inadequate income, housing, and health care needs, and although potentially harmful, the consequences of unmet physical activity need remain unknown.

2.2.2 Factors associated with unmet physical activity need

Many factors may contribute to older people's poor perceived opportunities for physical activity participation, such as competing interests, physical limitations and difficulties in accessing exercise facilities (Franco et al. 2015). Especially among those with mobility limitations, poor health, fear or negative experiences and an unsuitable environment are commonly perceived as barriers to physical activity (Rasinaho et al. 2007). Previous studies on the perception of unmet physical activity need in old age have found that it is more commonly encountered among older people who have musculoskeletal diseases and depressive symptoms (Rantakokko et al. 2010). Furthermore, another study targeting unmet physical activity need found that the accumulation of several different risk factors, including poor health and mobility limitations, considerably increased the risk for unmet physical activity need (Eronen et al. 2012).

While previous cross-sectional observations showed that older people with low physical activity levels were more likely to report unmet physical activity need (Eronen et al. 2012), the longitudinal associations between physical activity and unmet physical activity need remain unknown. However, in an earlier study, older people experiencing unmet physical activity need reported that they had recently reduced their level of physical activity (Rantakokko et al. 2010). Thus, it is plausible that an unwanted decrease in physical activity level precedes the development of unmet physical activity need. It has been suggested that unmet physical activity need is probably transient, and that older people adapt to lower levels of physical activity if their opportunities for physical activity participation are not improved (Rantakokko et al. 2010). Older people experiencing unmet physical activity need thus form an important target group for interventions aiming at promoting physical activity and equal opportunities for participation in physical activity. Modifications in walking such as taking breaks, slowing down, or using an aid may decrease the risk for developing unmet physical activity need (Skantz et al. 2019). From a theoretical perspective, unmet physical activity need can result from person-environment misfit, where environmental support for physical activity is no longer sufficient to meet the person's capabilities (Lawton & Nahemow 1973).

2.3 Sleep, fatigue and fatigability

2.3.1 Sleep characteristics and their contribution to health

Sleep is a state that can be differentiated from wakefulness based on behavioral criteria and electrical activity in the brain (Chokroverty 2010). It can be defined as follows: "Sleep is a recurring, reversible neuro-behavioral state of relative perceptual disengagement from and unresponsiveness to the environment. Sleep is typically accompanied (in humans) by postural recumbence, behavioral quiescence, and closed eyes." (Carskadon & Dement 2005). The two-process model of sleep regulation posits that the sleep-wake rhythm of humans is regulated by circadian and homeostatic processes (Borbély 1982; Borbély et al. 2016). The circadian rhythm is "paced" by the suprachiasmatic nucleus (SCN), which is located in the hypothalamus. All the tissues and organs in the body have their own circadian clocks which are regulated by the SCN (Banks, Nolan & Peirson 2016). The circadian rhythm is roughly, but not exactly, 24 hours and is dependent on photic and non-photic external cues to be synchronized with a 24-hour day. In the absence of external cues, the circadian clock will start to free run. The timing of external cues is also important: for example, light exposure at the wrong time of day could lead to circadian advancement or delay (Baron & Reid 2014). Physical activity could also function as an external cue and help in the synchronization of the circadian system (Buxton et al. 2003; Barger et al. 2004; Yamanaka et al. 2010). The homeostatic sleep drive accumulates during wakefulness and decreases during sleep. Longer time spent awake results in longer and deeper sleep to recover (Borbély 1982; Borbély et al. 2016). According to the model, these processes together determine how the sleep period is timed over a 24-hour period. Another model explaining sleep regulation is the three-oscillator model, which highlights the importance of circadian process in determining the sleep-wake rhythm. The model posits that three oscillators, namely the temperature, wake and sleep oscillators, determine how both sleep and wake are timed over 24 hours (Kawato et al. 1982).

Sufficient sleep is vital for health and wellbeing over the life course and is important for healthy aging. Poorer sleep characteristics are associated with several adverse health outcomes such as decreased health-related quality of life (Reid et al. 2006), the onset of several chronic conditions (Ancoli-Israel 2009), less disease-free life years (Stenholm et al. 2018) and mortality (Hublin et al. 2011). As well as having important implications for health, sleep also has immediate consequences that affect daytime performance (Bonnet 1985). Sleep deficiency is a general term describing poor sleep in one of its dimensions, but it is independent of diagnosed sleep disorders. Sleep deficiency can be described as a discrepancy in sleep duration, quality or timing compared to what is needed for optimal health and performance, and thus sleep is considered as a multidimensional construct (National Center on Sleep Disorders Research 2011). Sleep health is a newer concept that also highlights the multidimensional nature of sleep and wakefulness and their contribution to physical and mental wellbeing (Buysse 2014; Matricciani et al. 2018). Assessment of sleep health is multidimensional and can be divided into sleep satisfaction, timing, alertness, efficiency, and duration, all of which dimensions are important determinants of sleep health (Buysse 2014).

Sleep quality is also a multidimensional concept that is often used in studies but it lacks a unified definition (Krystal & Edinger 2008). Oftentimes, however, a set of objective measures of sleep characteristics, such as total sleep time, sleep onset latency, wake after sleep onset and sleep efficiency, are used to describe sleep quality (Krystal & Edinger 2008; Ohayon et al. 2017). Buyesse et al. (1989) described sleep quality as “a complex phenomenon that is difficult to define and measure objectively”, indicating that individuals’ subjective perception of sleep quality is important (Buysse et al. 1989). On the other hand, while asleep people are not consciously observing their sleep quality, a state which limits relying solely on self-reported measures of sleep quality (Ohayon et al. 2017). Regardless of the lack of a clear definition, sleep quality and its consequences on health and quality of life have been widely studied.

Optimal sleep duration varies greatly between individuals and is influenced by various factors such as age, sex and genetic factors (Ferrara & De Gennaro 2001; Chaput, Dutil & Sampasa-Kanyinga 2018). Although it has been recognized that some individuals have a lower and some a higher need for sleep than average (Ferrara & De Gennaro 2001), general recommendations of the optimal sleep duration have been made at the population level. The National Sleep Foundation recommends that older people should sleep approximately 7 to 8 hours per night (Hirshkowitz et al. 2015). Research has shown that sleep duration has a U-shaped association with adverse health outcomes. Both short (⩽5-7 h) and long (>8-9 h) sleep duration are associated with several adverse consequences, including less healthy life years, and higher risk of mortality (Hublin et al. 2007; Cappuccio et al. 2010a; Cappuccio et al. 2010b; Cappuccio et al. 2011; Stenholm et al. 2018). Sleep duration should be separated conceptually from time in bed. Time in bed can be defined as the time from when one goes to bed to the time when one gets out of bed in the morning (Meijer et al. 2010) and thus includes time spent awake as well as time spent asleep while lying in bed (Gabelle et al. 2017). Sleep duration, in turn, is defined as the time spent asleep (Meijer et al. 2010). In addition to sleep duration, short or long time in bed are associated adverse health outcomes. For instance, short time in bed is associated with depression (Furihata et al. 2015), while long time in bed predicted steeper decline in physical function (Stenholm et al. 2011). Although not directly being a measure of sleep, time in bed, as well as bedtimes and arising times, describe modifiable sleep-related behavior (Thomas et al. 2014; Furihata et al. 2015; Husu et al. 2021). Time in bed limits the time in which sleep can occur and for instance, a person with a short time in bed will also have short sleep duration (Shrivastava et al. 2014). Similarly, a person with an irregular time in bed will plausibly also have irregular sleep timing. However, Stenholm et al. (2011) found that self-reported sleep duration and time in bed were only moderately correlated and concluded that, although related, they should be considered as partly independent measures (Stenholm et al. 2011).

Although most studies targeting the health consequences of sleep have focused on sleep duration and quality (Matricciani et al. 2018), other aspects of sleep, such as its timing and regularity, have also important implications for health. For instance, in a recent systematic review, greater irregularity in sleep timing and later bedtime were found to be associated with several adverse health outcomes among adults (Chaput et al. 2020). Furthermore, disrupted circadian activity rhythms have been found to be associated with higher mortality risk in a large sample of older women (Tranah et al. 2010).

2.3.2 Age-related changes in sleep

With advancing age, sleep and the regulation of circadian rhythm go through several changes. Aging-related changes occur in sleep architecture and patterns.

The proportion of deep sleep decreases and the proportion of light sleep simultaneously increases (Ohayon et al. 2004). In addition, sleep latency increases and sleep can become more fragmented with advancing age (Ohayon et al. 2004). Older people tend to spend longer in bed during their nighttime rest (Thomas et al. 2014). In addition, the prevalence of sleep disturbances increases with advancing age. The increase in sleep disturbances with age seems to be related to the age-related increase in diseases and not to the normal aging process (Ancoli-Israel 2009).

Regulation of the SCN also changes with age. Circadian rhythms become weaker and responsiveness to external cues decreases (Lavoie, Zeidler & Martin 2018). The main change in the circadian system is reduced amplitude, as seen, for instance, in the regulation of body temperature and hormonal secretion (Van Someren 2000). In addition, sensitivity to external cues decreases and the resynchronization of the circadian system is slower (Dijk & Archer 2009, Lavoie, Zeidler & Martin 2018), and hence adaptation to changes in daily sleep schedules decreases. Other changes include an advance in the circadian rhythm, which results in earlier wake-up and bedtimes among older people (Dijk & Archer 2009, Lavoie, Zeidler & Martin 2018). These age-related changes in the circadian system, including the decreasing ability to adapt to these changes, could make older people more vulnerable to desynchronization of the circadian system and circadian misalignment (Lavoie et al 2018). Circadian misalignment refers to a situation where the sleep-wake rhythm is timed inappropriately. Irregular sleep patterns and delayed sleep timing could be signs of circadian misalignment and disrupted circadian rhythm, which may influence daytime function and lead to health decline (Baron & Reid 2014).

Sleep is usually assessed in studies with both self-report and objective assessment methods. The golden standard for sleep measurement is polysomnography (PSG), which includes electrophysiological monitoring (Marino et al. 2013). PSG allows for assessment of the physiological properties of sleep and the sleep architecture (Vallières & Morin 2003, Redeker, Pigeon & Boudreau 2015). PSG is, however, costly and requires special training (Redeker, Pigeon & Boudreau 2015). Sleep can also be measured with actigraphy. The advantage of actigraphy over PSG is that measurement can be continued for days or even weeks (Ancoli-Israel et al. 2003, Redeker, Pigeon & Boudreau 2015). Actigraphy is more affordable than PSG and allows the continuous measurement of activity and sleep (Redeker et al. 2015). Sleep is often assessed using a wrist-worn device as it may be the best location for detecting small distal movement (Ancoli-Israel et al. 2003). Wrist-worn devices, however, are not ideal in assessing physical activity or sedentary behavior, and they do not allow assessment of body posture (Quante et al. 2015). Furthermore, while thigh-worn devices cannot be used to assess sleep, they can provide relatively accurate estimated of bed- and arising times, and time in bed (van der Berg et al. 2016; Winkler et al. 2016, Courtney et al. 2020). Actigraphy may, furthermore, overestimate sleep duration, since sleep assessment is based on non-movement (Marino et al. 2013; Redeker, Pigeon & Boudreau 2015), and can thus be confused with lying in bed awake or sedentary behaviors performed in bed (Gibbs & Kline 2018). In addition, self-reported questionnaires have been developed for the assessment of several aspects of sleep. One of the most widely used questionnaires is the Pittsburgh Sleep Quality Index, which includes questions on, for instance, perceived sleep duration, sleep onset latency and impaired daytime function (Buysse et al. 1989). Self-reported sleep questionnaires are affordable and do not overly burden study participants. Self-reported measures of sleep, however, do not strongly correlate with objectively measured sleep. Subjective measures, such as sleep diaries often overestimate sleep latency compared to objective measures (Vallières & Morin 2003). People with poorer sleep may also underestimate their sleep duration compared to objectively measured sleep duration (Vallières & Morin 2003; Van Den Berg et al. 2008). In contrast, good sleepers may overestimate their sleep duration compared to objectively measured sleep duration (Silva et al. 2007; Matthews et al. 2018).

2.3.3 Fatigue and fatigability in old age

Fatigue is a complex and multifactorial symptom, which can be characterized as an unpleasant symptom that interferes with an individual's ability to function at their normal level and manifests as feelings ranging from tiredness to exhaustion (Ream & Richardson 1996). Another definition of fatigue is a subjective lack of physical and/or mental energy that is perceived to interfere with usual or desired activities (Alexander et al. 2010). Although the terms fatigue and sleepiness have quite often been used interchangeably, they describe two different phenomena (Dinges 1995; Shen, Barbera & Shapiro 2006). As opposed to fatigue, sleepiness can be characterized as an increased propensity to fall asleep (Shen, Barbera & Shapiro 2006). While fatigue is a commonly reported symptom of several mental and physical diseases, such as cancer, many older people report fatigue with no clear underlying cause (Avlund 2010). Persistent fatigue can have severe negative consequences on health and functioning. Fatigue related to mobility tasks has been considered one indicator of preclinical disability (Mänty et al. 2007). Furthermore, fatigue is one of the early determinants of frailty, and persistent fatigue can arise already years before the onset of frailty (Stenholm et al. 2019). Fatigue may represent an early phase of frailty before its functional consequences have emerged (Avlund 2010).

Fatigue is a common symptom among older people. Although commonly reported, the prevalence of fatigue varies substantially between different studies. In a large study comparing 10 European countries, the prevalence of fatigue among older people varied from 28% in Austria to 55% in Spain (Santos-Eggimann et al. 2009). In a study targeting older people living in a residential care facility, the prevalence of fatigue symptoms was as high as 98% (Liao & Ferrell 2000). Findings on whether fatigue increases with advancing age are also conflicting. In a large German sample, the prevalence of fatigue was found to be consistently higher in the older age groups among both men and women (Beutel et al. 2002; Beutel et al. 2004). Conversely, other studies have found no age-related increase in fatigue (Stone et al. 2008; Christie, Seery & Kent 2016). The reason for these conflicting findings may in part be due to the wide variety of measures as well as to potential self-pacing bias – older people who experience greater fatigue in response to daily activities may engage in adaptive behaviors in an attempt to avoid fatigue, such as pacing and avoiding fatigue-inducing activities (Eldadah 2010; Kratz et al. 2019). As a response to this, the concept of fatigability has been recognized as a phenotype of fatigue and has been increasingly studied among older people during the past decade. Fatigability can be characterized as fatigue related to a specific task, standardized by duration and intensity (Eldadah 2010), and thus can be controlled for potential self-pacing bias. Fatigability can be described as the process of feeling fatigued while engaging in a given activity (Kratz et al. 2019). Although fatigability has been of interest in physiology research for a longer time, interest in fatigability as a whole-body construct has come to occupy researchers more recently, during the past decade (Schrack, Simonsick & Glynn 2020). Fatigability provides a measure that anchors the feeling of fatigue to different standardized activities and can therefore describe how older people may be restricted in their daily activities due to fatigue. Indeed, it seems that fatigue related to daily activities is exceedingly common in old age and its prevalence accelerates with advancing age. In a Danish study, over half of the participants experienced fatigue related to daily activities at age 70, whereas at the age of 85 the proportion was close to 80% (Avlund 2010). Fatigability has been thought to be a dynamic process rather than an irreversible situation, and thus many factors can influence the process of becoming fatigued when performing different activities (Kratz et al. 2019).

2.3.4 Dimensions of fatigability

Perception of fatigue can be divided into three dimensions: physical, mental, and emotional (Kratz et al. 2019). In a recent study conceptualizing fatigability, participants described physical fatigue as lack of physical energy or feeling physically drained. Mental fatigue was described as feeling mentally tired or lacking energy to think. Emotional fatigue, in turn, was described as feelings of being overwhelmed, exhausted, or defeated. The same dimensions can be applied in the case of fatigability (Kratz et al. 2019). So far, physical fatigability seems to be the dimension that has been most studied among older people, although the measurement of mental fatigability among older people has also been targeted (Glynn et al. 2015). It has also been suggested that the perception of fatigue can cross domains, and therefore a task that is considered as predominantly physical could also lead to mental and physical fatigue (Kratz et al. 2019). Similarly, many activities can be considered as physically, mentally, and emotionally demanding at the same time (Kratz et al. 2019).

As well as the physical, mental, and emotional dimensions, the measurement of fatigability has often been operationalized as perceived fatigability and performance fatigability (Kluger, Krupp & Enoka 2013). Perceived fatigability refers to a person's perception of their own level of fatigability in relation to a standardized task and is frequently used in studies targeting older people (Kluger, Krupp & Enoka 2013; Schrack, Simonsick &

Glynn 2020). Perceived fatigability can be measured with fully self-reported questionnaire-based assessment methods, which typically include assessment of the level of fatigue in relation to a list of activities described by duration and intensity (Yang & Wu 2005; Glynn et al. 2015), or by self-reports after completing a standardized task (Simonsick et al. 2014). Performance fatigability, in contrast, is a more objective assessment method. It refers to a decline in performance related to a standardized task (Kluger, Krupp & Enoka 2013). For instance, two people may perform the same walking test with a standardized duration and speed. One of them may maintain a similar speed throughout the test whereas, to be able to finish the test, the other slows down. In this example, the latter person would be deemed to experience higher performance fatigability. Although performance fatigability is usually measured during a test at a standardized pace (Van Geel et al. 2019), assessing performance fatigability using a self-selected pace may better reflect fatigability in daily life situations (Schnelle et al. 2012). This may be especially true for older people. Although measures of performance fatigability have been developed and validated for self-paced walking tests (Schnelle et al. 2012; Murphy, Kratz & Schepens Niemiec 2017), these tests seem to provide higher scores for people who, contrary to the definition of performance fatigability, increase rather than decrease their walking speed during the test. Measures of performance fatigability among older people therefore warrant further development.

2.3.5 Associations of sleep and fatigue with physical activity participation

An association between sleep and physical activity has consistently been found. A wide range of studies have reported that both regular and acute physical activity is beneficial for various aspects of sleep (Kredlow et al. 2015; Vanderlinden, Boen & van Uffelen 2020). Regular physical activity engagement has also been shown to have a beneficial association with sleep among people with sleep deficiencies (Yang et al. 2012). Furthermore, a greater amount of daily physical activity is associated with time in bed (Gabriel et al. 2017) and an earlier bedtime (Breneman et al. 2019) the same night. Other studies have targeted the bidirectional association between sleep and physical activity, showing that better sleep enhances physical activity participation (Lambiase et al. 2013; Dzierzewski et al. 2014; Holfeld & Ruthig 2014). Holfeld & Ruthig (2014) found that better baseline sleep quality predicted higher physical activity levels over time, whereas baseline physical activity levels did not predict sleep quality. In contrast, Mesas and colleagues found no associations of baseline sleep characteristics with physical activity over time (Mesas, Hagen & Peppard 2018). Tsunoda and colleagues (2015) and Mesas and colleagues (2018) found that higher physical activity levels prevented insufficient sleep over time among older people. Thus, although there is an association between physical activity and sleep, the relationship between the two behaviors among older people is not yet thoroughly understood. Furthermore, while research has often focused on the associations of physical activity with sleep measures such as total sleep time, sleep fragmentation and sleep quality, far fewer studies have focused on the associations of physical activity with sleep timing or regularity, although these seem to be related. A recent systematic review found that earlier sleep timing and regular patterns of sleep were associated with higher physical activity levels among adults (Chaput et al. 2020). Another previous cross-sectional study on older people found that irregular sleep patterns were associated with lower physical activity levels (Lunsford-Avery, Engelhard & Navar 2018).

One of the potential reasons for the association of poor sleep on physical activity participation is fatigue (Groeger, Zijlstra & Dijk 2004; Holfeld & Ruthig 2014; Gilbert et al. 2018). In study with a large sample of people with osteoarthritis, the association of restless sleep and lower physical activity levels were greatly attenuated after controlling for fatigue (Gilbert et al. 2018). Fatigue has been reported to be one of the independent consequences of sleep disturbances (Hossain et al. 2005), and disturbed sleep has been found to predict persistent fatigue that limits daily activities (Endeshaw 2015). Poor sleep quality, early morning awakenings and short sleep duration are associated with higher daytime fatigue (Alapin et al. 2000; Goldman et al. 2008; Hawker et al. 2010; Christie, Seery & Kent 2016), poorer concentration and higher sleepiness among older people (Alapin et al. 2000). Among patients with sleep disturbances, pathological fatigue was commonly reported even in the absence of sleepiness (Hossain et al. 2005). Poorer sleep has also been associated with higher levels of perceived physical fatigability (Aldughmi et al. 2016; Alfini et al. 2020) and considered to be one of the causes of higher mental fatigability (Kratz et al. 2019). Fatigue, in turn, has been found to be one of the frequently reported barriers to physical activity (Cohen-Mansfield, Marx & Guralnik 2003; Wilcox et al. 2006; Kowal & Fortier 2007) and a reason for restricted activity among older people (Gill et al. 2001). Fatigue has been characterized as a debilitating symptom and state of energy depletion that can force older people to pace an activity and hinder their opportunities to participate in activities (Yu et al. 2010). Among older people living in a health care facility, the pacing of different activities was reported as the most common adaptive method to cope with fatigue (Toye, White & Rooksby 2006). Higher levels of perceived physical fatigability have also been associated with lower accelerometer-based physical activity throughout the day (Wanigatunga et al. 2017). Although fatigue itself can be considered an important barrier to physical activity, low physical activity levels also predict increased fatigue levels (Martin et al. 2006). The presence of sleep deficiency, higher fatigue and lower physical activity levels could thus lead to a cycle of even poorer sleep, higher fatigue, and lower physical activity.

So far, several studies have also linked both poor sleep and activity-related fatigue with physical function, which in turn may further limit older people's opportunities for physical activity participation. Findings show that short sleep, poorer sleep quality and more nighttime awakenings are associated with poorer physical function (Goldman et al. 2007; Dam et al. 2008; Stenholm et al. 2010; Reyes et al. 2013; Chien, Meng-Yueh & Chen 2015). Among older men, long sleep duration was also associated with poorer physical function (Dam et al. 2008). In a longitudinal study, Stenholm et al. (2011) found that both long sleep duration and long time in bed independently predicted a steeper functional decline over time. Short sleep duration has also been found to be associated with poorer physical function (Stenholm et al. 2010, Lorenz et al. 2014), with both long objectively measured sleep duration and short subjective sleep duration predicting a steeper functional decline among older people (Stenholm et al. 2011).

Fatigue has negative consequences on health and functioning. Fatigability has been shown to predict impending mobility decline (Simonsick et al. 2016). Fatigability has been suggested to be an early indicator of age-related decline in physical function, as higher fatigability levels have been found to precede functional decline among high-functioning older people (Simonsick et al. 2016). Previous studies have shown that mobility-related and general fatigue are associated with lower levels of physical activity (Egerton et al. 2016) and predict walking limitations (Avlund et al. 2004), decline in physical function and disability over time (Avlund et al. 2002; Schultz-Larsen & Avlund 2007; Manty, Kuh & Cooper 2015).

One explanation for the age-related increase in fatigability is thought to be deficits in energy production and utilization (Eldadah 2010, Alexander et al. 2010). Energy is need for maintaining the resting metabolic rate (RMR), food thermogenesis, and physical and cognitive activities. Although the RMR is reported to decrease with advancing age, maintaining homeostasis with an increasing disease burden may require extra energy (Ruggiero et al. 2008; Alexander et al. 2010; Ferrucci et al. 2012). Simultaneously the energetic cost of activities increases with advancing age (Schrack et al. 2012). This may lead to energy deficit with not enough energy available for physical activities. Several cross-sectional studies have supported this hypothesis by showing that higher fatigability is associated with slow gait and higher energetic cost of walking (Richardson et al. 2014, Barbosa et al. 2016). Recently, Schrack and colleagues (2020) showed that higher energetic cost of slow walking and higher energetic cost combined with lower energetic capacity predicted higher perceived physical fatigability over time. Although higher perceived physical fatigability has been found to precede functional decline (Simonsick et al. 2016), the higher energetic cost of movement related to functional limitations could further accelerate fatigability (Wert et al. 2010, Wert et al. 2013). Both sleep and fatigue may have grounds in energy regulation. Although the functions of sleep are not thoroughly understood, one important function of sleep has been theorized to be energy conservation (Berger & Phillips 1988), and restoration (Adam & Oswald 1983). Both of these theories are in line with the findings that physical activity is beneficial for sleep, as both posit that slow-wave sleep will increase following increased energy expenditure induced by physical activity (Driver & Taylor 2000). Furthermore, fragmented sleep and prolonged wakefulness both disturb energy conservation and are associated with higher energetic needs at nighttime (Bonnet, Berry & Arand 1991; Jung et al. 2011). The failure to achieve sufficient and restorative sleep may therefore also limit the energy that is available for physical activity participation.

2.3.6 Theory of energy cost minimization

Several theories over the years have made an effort to explain physical activity participation. These theories include social cognitive, humanistic, dual-process and socioecological frameworks (Rhodes, McEwan & Rebar 2019). A recent dual-process approach aiming to explain physical activity participation is the theory of energy cost minimization (TECM) (Cheval et al. 2018; Cheval et al. 2019). The theory stems from the evolutionary perspective that humans have a natural tendency to avoid unnecessary physical exertion and conserve energy. While physical activity itself has been assumed to be rewarding, at least for physically active individuals, sedentary behavior can also be regarded as rewarding from the perspective of energy conservation. This underlying tendency may hinder participation in physical activity despite a conscious effort to be more physically active. Furthermore, the theory posits that cognitive resources are needed to counteract the natural tendency to avoid physical exertion (Cheval et al. 2018).

The TECM aims to explain the exercise paradox; many people know the benefits of physical activity and the harmful consequences that physical inactivity may have and yet continue to lead a physically inactive lifestyle. The automatic process of avoiding physical exertion could explain how people adjust their movement behavior to reduce the energetic cost (Selinger et al. 2015). A similar tendency may explain why older people may automatically compensate for the age-related increase in energetic cost of daily activities by slowing down or by pacing behavior in response to increasing fatigability (Eldadah 2010; Kratz et al. 2019).

2.3.7 The associations between sleep, fatigability, and physical activity from the energetic perspective

Fatigue related to daily activities has been recognized as an important early indicator of functional decline and loss of mobility. Fatigue has been considered to be indicative of the age-related decline in reserves and intrinsic capacity (Alexander et al. 2010) and fatigue symptoms may seriously hinder older people's opportunities for physical activity. As described in the previous section, one of the causes of age-related increase in fatigue is thought to be related to energy regulation (Alexander et al. 2010, Eldadah 2010).

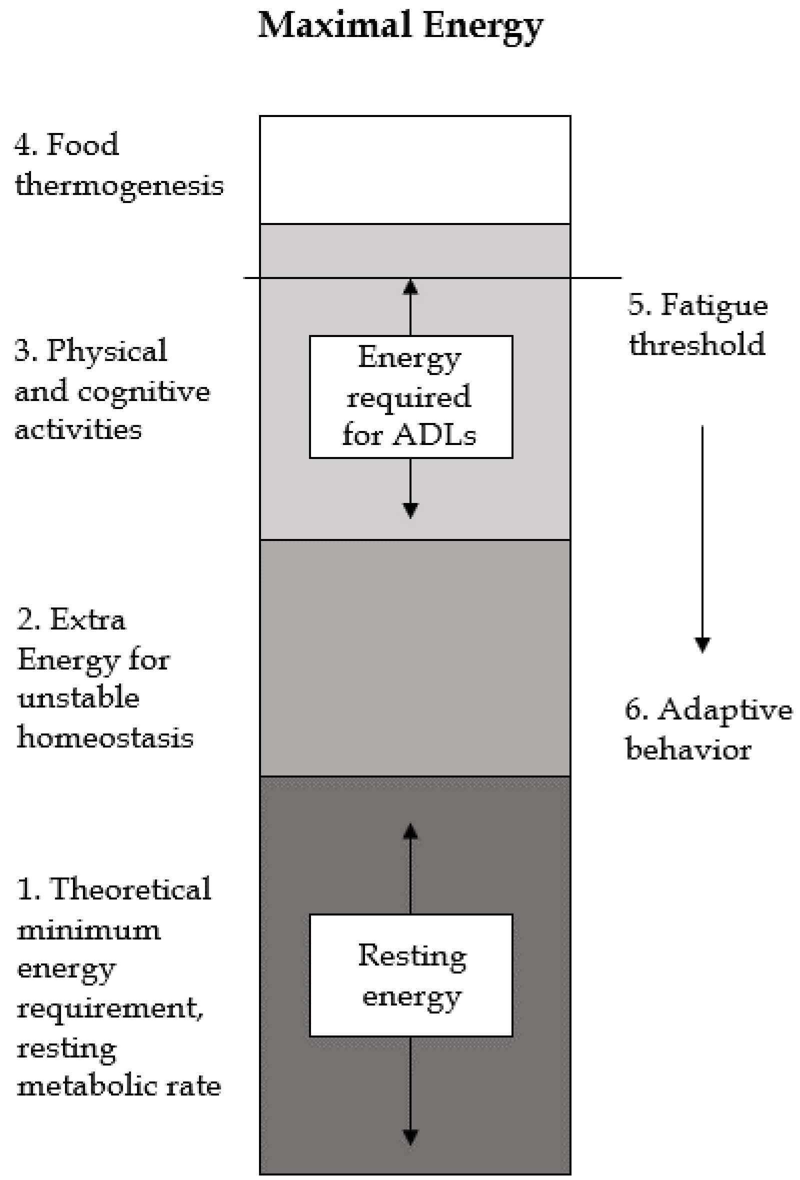

FIGURE 1 The extended model of aging energetics (modified from Schrack, Simonsick & Ferrucci 2010). 1. represents the resting metabolic rate, 2. represents the extra energy that is needed for unstable homeostasis due to comorbidities, 3. represents the energy that is needed for performing daily activities, and 4. represents the energy needed for food absorption and thermogenesis. With advancing age, energy available for daily activities may decrease, leading to greater feelings of fatigue (5.) and to adaptive behaviors in an attempt to maintain fatigue at an acceptable level (6.).

Various pathologies can underlie fatigability that may lead to functional limitations and, further, to disability (Verbrugge & Jette 1994). Both personal and environmental factors are important in disability progression. The extended model of aging energetics expands the theoretical approach to the progression of disability in old age by describing how the energy available to a person is associated with fatigue and adaptive processes such as reduced physical activity and gait speed, and eventually mobility loss (Figure 1). The model posits that, as the overall daily level of available energy decreases with age (Schrack, Simonsick & Ferrucci 2010), the energy needed to perform daily activities may simultaneously increase due to the aging-related increase in comorbidity and functional limitations (Hortobágyi et al. 2003; Schrack, Simonsick & Ferrucci 2010). In consequence, older people may have less energy available for daily activities, including physical activity. As a person approaches their maximum energy capacity, irrespective of what the maximum value is, feelings of fatigue will emerge. Feelings of fatigue, in turn, often lead to adaptive processes such as a slowing of pace in an attempt to remain within a safe margin of the maximum energetic limit (Schrack, Simonsick & Ferrucci 2010). Many studies have since provided support for parts of this theoretical model. Research has already shown that having less available energy is associated with lower physical activity levels (Schrager et al. 2014), while higher energetic cost of walking predicts a steeper decline in gait speed (Schrack, Zipunnikov et al. 2016). Older adults with slower preferred gait speed are likely to have reduced aerobic capacity, higher energetic cost of walking and higher fatigability (Richardson et al. 2014), supporting the view that slowing down is an adaptive compensatory response to having insufficient available energy and the resulting feelings of fatigue. Perceiving higher fatigability is associated with a higher energetic cost of walking (Barbosa et al. 2016), which in turn predicts a slowing down of gate speed over time (Schrack, Zipunnikov et al. 2016). Conditions such as pain can also decrease energy efficiency and increase the energetic cost of walking among older people and are thus also associated with slower gait speed (Ko, Simonsick & Ferrucci 2015). The extended model of aging energetics is closely related to the concept of fatigability and explains how increasing fatigability may be associated with adaptive processes aimed at remaining below the fatigue threshold (Alexander et al. 2010). Adaptive processes initiated when facing impending fatigability can potentially be seen in more fragmented patterns of accumulating daily physical activity (Schrack et al. 2019).

Another, more recent approach to explaining how fatigability may limit physical activity participation is the conceptual model of fatigability (Kratz et al. 2019). This model also aims to explain how fatigability leads to the adoption of adaptive strategies and a reduction in physical activity levels (Figure 2). In the model, the process of perceiving fatigue related to different physical, mental and emotional activities is described as fatigability. How fatigability is perceived is moderated by different individual factors that are either trait- or state-like. Trait-like factors, such as comorbidity, age, and physical fitness, are relatively stable whereas state-like factors are shorter term conditions that can affect how susceptible a person is to feelings of fatigue, such as acute pain, poor sleep quality and lack of motivation. Feelings of fatigue then affect engagement in further activities, a state that is described as fatigue impact. People who are susceptible to higher fatigability engage in different proactive and reactive behaviors to avoid or adapt to levels of fatigue (Kratz et al. 2019). Thus, susceptibility to higher fatigability is not necessarily a long-term condition, and its magnitude is the outcome of different factors.

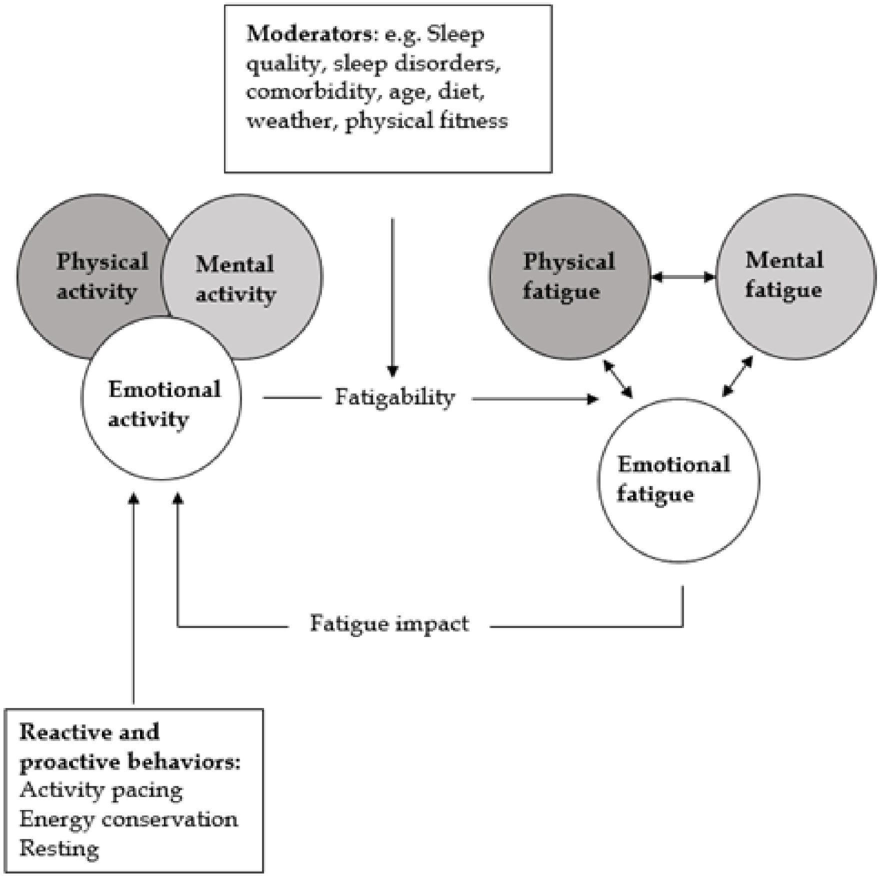

FIGURE 2 Conceptual model of fatigability (modified from Kratz et al. 2019).

The extended model of aging energetics and the conceptual model of fatigability both aim to explain how older people with higher fatigability may have to limit their physical activity participation. A previous study already showed that older adults with higher perceived fatigability are more likely to engage in lower levels of physical activity throughout the day (Wanigatunga et al. 2017). Furthermore, it may be that early adaptive processes related to increasing levels of fatigability manifest as a more fragmented pattern of accumulating daily physical activity (Schrack et al. 2019), and may thus indicate pacing behavior. It is plausible that persons who, due to increasing levels of fatigability, have to modify and limit their physical activity against their own will are more likely to experience unmet physical activity need.

2.4 Theoretical framework of the study

The framework of this study is illustrated in Figure 3. It is based on the extended model of aging energetics (Schrack, Simonsick & Ferrucci 2010) and the conceptual model of fatigability (Kratz et al. 2019).

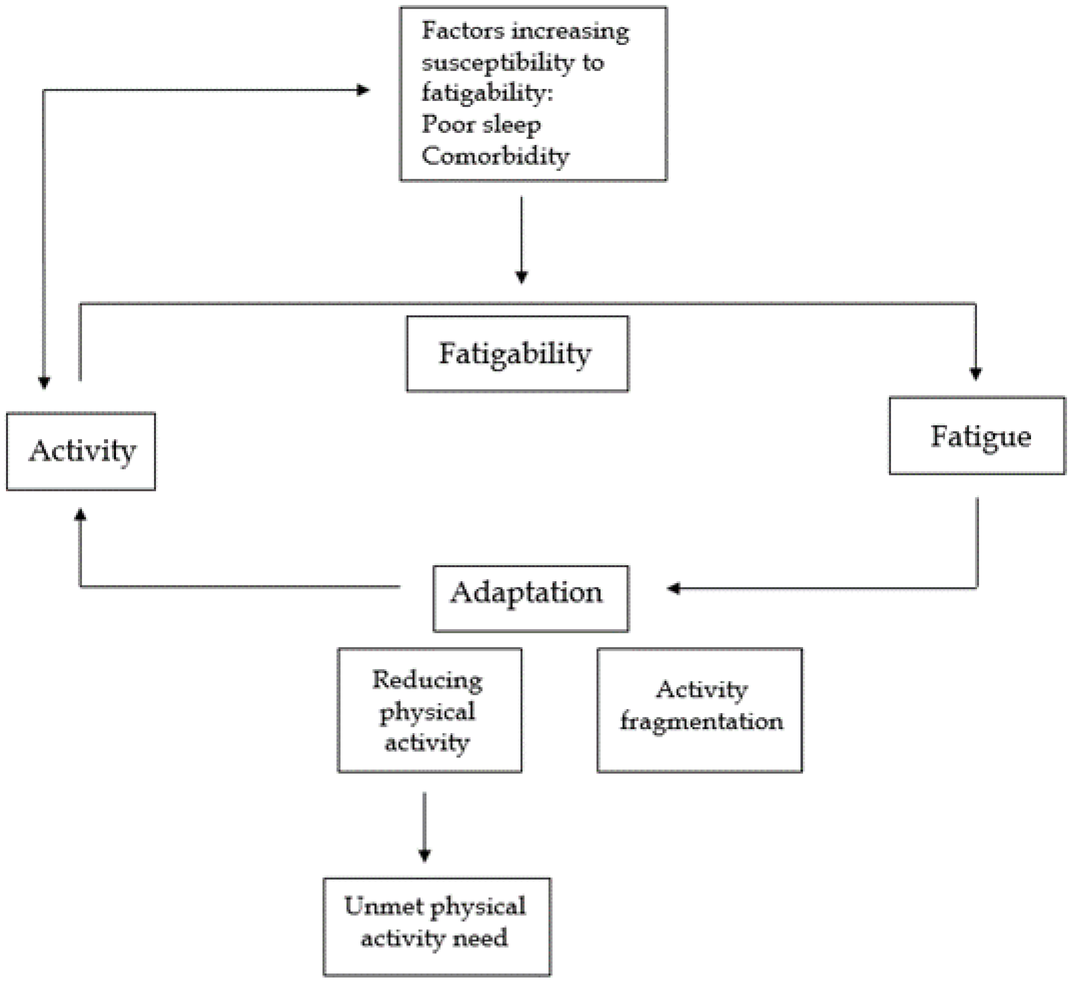

FIGURE 3 Conceptual framework of the study.

The association of poor sleep with poorer opportunities for physical activity participation and unmet physical activity need may result from a higher susceptibility to fatigue after insufficient and nonrestorative sleep. People who experience higher fatigability are likely to adopt different adaptive behaviors to alleviate and cope with fatigue (Kratz et al. 2019). Early strategies to alleviate fatigue related to walking and other physical activities may be taking breaks and slowing down. This behavior can potentially be seen as more fragmented patterns of physical activity accumulation in accelerometer-based physical activity data (Schrack et al. 2019). These adaptive strategies may allow older people to accumulate relatively high levels of physical activity despite impending fatigability. When pacing behavior is no longer sufficient to alleviate fatigue, people may start to avoid activities that cause them fatigue and may be forced to reduce their level of physical activity (Egerton et al. 2016, Wanigatunga et al. 2017). If the reduction in physical activity level is unwanted, people may feel distress over the loss of a valued activity and thus experience unmet physical activity need. Reduced physical activity levels may then lead to poorer sleep and increased fatigue (Martin 2006) and susceptibility to fatigue (Alexander et al. 2010). Age-related diseases also contribute to poor sleep (Ancoli-Israel 2009) and reduce the opportunity to engage in physical activities. The coincidence of poor sleep, fatigue and low physical activity could therefore lead to a negative cycle which exacerbates sleep deficiencies and fatigue and further limits physical activity participation.

Although no previous study has targeted fatigue and unmet physical activity need, fatigue has been found to be a determinant of physical activity participation (Wilcox et al. 2006; Wanigatunga et al. 2017) and is thus likely to predispose older adults to unmet physical activity need. Older people with poor sleep are more likely to experience higher general fatigue (Hossain et al. 2005; Goldman et al. 2008) and be more susceptible to feeling fatigued when performing daily activities (Aldughmi et al. 2016; Alfini et al. 2020). Thus, poor sleep together with higher levels of fatigue may be substantial barriers to physical activity and lead to unmet physical activity need among older people.

3 AIMS OF THE STUDY

The first aim of this dissertation was to study whether fragmented physical activity patterns are associated with poorer sleep characteristics and higher physical and mental fatigability in older people. The second aim was to study whether higher fatigue, higher fatigability and poorer sleep characteristics are associated with unmet physical activity need in old age. Finally, the third aim was to study whether lower physical activity levels and higher fatigue precede the development of unmet physical activity need over time. The specific research questions were:

1. Are more fragmented physical activity patterns associated with poorer sleep characteristics and higher physical and mental fatigability among community-dwelling older people?

2. Are higher fatigue, higher fatigability and poorer sleep characteristics associated with unmet physical activity need among older people?

3. Do lower physical activity levels, lower neighborhood mobility and higher fatigue predict the development of unmet physical activity need?

The first research question is addressed in Studies II and III with a cross-sectional study design. The second research question is addressed in Study IV and additional unpublished analyses with a cross-sectional study design. Finally, the third research question is addressed in Study V and additional unpublished analyses with longitudinal data.

4 METHODS

4.1 Datasets and study designs

This study utilized data from three larger study projects. These were the Finnish Twin Study on Aging (FITSA), the Life-Space Mobility in Old Age (LISPE) study and the Active Ageing – Resilience and External Support as Modifiers of the Disablement Outcome (AGNES) study.

4.1.1 Active Aging – Resilience and External Support as Modifiers of the Disablement Outcome (AGNES, Studies I, II & III)

AGNES was a large research project conducted in 2017-2019 in the city of Jyväskylä, in central Finland. Participants were samples of three cohorts of 75-, 80-, and 85-year-old people. The total sample of 2 791 was drawn from the Finnish population register. Of this initial sample, 2 348 individuals were asked by telephone if they would be willing to take part. Inclusion criteria were age and residence in the study area, willingness to participate and the ability to communicate (Rantanen et al. 2018). After exclusions, 1 021 individuals participated in the study. Of these, 495 wore a tri-axial accelerometer, and 452 wore two tri-axial accelerometers for 7 to 10 consecutive days after a face-to-face home interview. In addition, participants completed a postal questionnaire and participated in assessments at the research center.

In Study I, for the initial validation of the performance fatigability scale and additional analyses on the associations between fatigability and unmet physical activity need, the participants comprised all those with valid data on performance fatigability (n=778). Study II comprised participants with at least three days of valid data on sleep-related characteristics (time in bed, bedtimes and arising times) and activity fragmentation (n=351) and Study III comprised participants with at least 3 days of valid accelerometer data (n = 485).

4.1.2 Finnish Twin Study on Aging (FITSA, Study IV)

The FITSA study is a prospective study targeting older twin women. The FITSA sample, which had originally been recruited from the national population register, was drawn from the Finnish Twin Cohort Study. The initial inclusion criteria for the FITSA study were age, sex, zygosity and willingness to participate in the study by both twin sisters. A total of 434 twin women participated in the first study wave in 2000-2001 (Pajala et al. 2004). When the concept of unmet physical activity need was introduced in 2010, the items on unmet physical activity need were incorporated only into the third FITSA study wave, which was implemented in 2011-2012. Therefore, only data from the third study wave was utilized in the present study (N=344). At the time of data collection, participants were 74-86 years old. Data were collected with postal questionnaires, supplemented with a phone interview in cases where the participant had difficulties in answering the postal questionnaire (Viljanen et al. 2013). Study IV only included participants (N=302) who had data on unmet physical activity need.

4.1.3 Life-Space Mobility in Old Age (LISPE, Study V)

The LISPE study was a two-year prospective cohort study. Data were collected between the years 2012 and 2014 in the city of Jyväskylä, in central Finland. Participants were 75- to 90-year-old community-dwelling men and women. A random sample of 2 550 was initially drawn from the Finnish population register based on age and residency in the Jyväskylä area. The initial inclusion criteria included willingness to participate, living in the recruitment area independently, and the ability to communicate sufficiently. A total of 848 people met these criteria and participated in the study (Rantanen et al. 2012). The study protocol included a home interview at baseline and follow-up phone interviews at one and two years thereafter. Of the initial sample, 816 individuals participated in the one-year follow-up and 761 in the two-year follow-up (Rantakokko 2016).

In addition, at baseline, a subgroup of 174 participants agreed to wear an accelerometer for seven days. Study V only included participants who did not report unmet physical activity need at baseline but subsequently reported unmet physical activity need at least one of the two follow-ups, resulting in a total of 700 participants including 156 participants from the accelerometer substudy.

4.2 Ethics

The FITSA, LISPE and AGNES studies were all conducted according to the principles of good scientific practice laid down by the Declaration of Helsinki. The ethical committee of the Central Finland Health Care District approved FITSA and AGNES studies. The ethical committee of the University of Jyväskylä, Finland approved the LISPE study. Participants were informed about the study both verbally and in writing, and all participants provided a written informed consent prior to participation. Participation in all of the studies was voluntary and the participants had the right to withdraw their consent at any time during the study. All data was pseudonymized for the analyses and only members of the research group had access to the data. All digital data were stored securely on the university server and protected by passwords.

4.3 Measurements

4.3.1 Self-reported sleep characteristics

Self-reported sleep duration and sleep quality were assessed in the FITSA study (Study IV). Sleep duration was assessed with a single question: "How many hours on average do you habitually sleep per night?" Response options were categorized into short (<6 hours), normative (6-8 hours) and long (>8 hours). This categorization was based on a previous categorization of short and long sleep duration among older people (Chien, Wang & Chen 2015).

Self-reported sleep quality was assessed with a single question: "How well do you usually sleep?" Response options were "well", "quite well", "quite poorly", "poorly" and "not sure". For further analyses, the response options were dichotomized into "well" (quite well and well) and "poor" (quite poorly and poorly). Participants whose response was "not sure" (n=7), were excluded from the corresponding analyses.

Restless sleep was derived from the Center for Epidemiologic Studies-Depression scale (CES-D) (Radloff 1977) and was assessed in the AGNES and LISPE studies (unpublished analyses). Participants asked to rate how often they experienced restless sleep during the past week. The response options were "rarely or none of the time", "some or a little of the time", "occasionally or a moderate amount of time", and "all of the time". Participants who answered either occasionally or a moderate amount of time, or all of the time were considered as having restless sleep.

4.3.2 Accelerometer-based sleep-related behaviors

Accelerometer-based sleep-related behaviors were assessed in the AGNES study and used in Study II. One accelerometer (range ±16 g, 13-bit analog-to-digital conversion, sampled at 100 Hz, UKK RM42, UKK Terveyspalvelut Oy, Tampere, Finland) was placed on the participant's dominant thigh and the other (range ±16 g, 14-bit analog-to-digital conversion, sampled at 100 Hz, eMotion Faros 180, Bittium Corporation, Oulu, Finland) on either the participant's sternum or left side of the chest (Portegijs et al. 2019). Recordings from both accelerometers were processed with the same protocol. Body postures were estimated for each 5-s epoch and categorized into lying, sitting and upright using a threshold adapted from Vähä-Ypyä and colleagues (2018). The categorization was based on the following criteria: lying if both accelerometers indicated an angle > π/4, sitting if the thigh-worn accelerometer indicated an angle > π/4 and trunk-worn indicated angle of ≤ π/4 and upright if both accelerometers indicated an angle of ≤ π/4.

Bedtimes and arising times were detected from accelerometer recordings following an automated approach proposed by van der Berg and colleagues (2016), which has been shown to have a relatively high agreement with self-reported bed and wake times (van der Berg et al. 2016; Courtney et al. 2020). Briefly, bedtimes were determined by summing up consecutive bouts of lying down and comparing them against pre-set time-based cut-off values depending on the start of the first bout. When the sum exceeded the pre-determined cut-off value, bedtime was determined at the start of the first lying down bout. Similarly, arising times were determined based on summing up active bouts and comparing them against pre-set cut-off values which were based on time. Time in bed was then calculated as the time between bedtime and the final arising time. The original algorithm was slightly modified, so that time in bed was restricted to lying down rather than allowing either sitting or lying down postures. During time in bed, the approach allowed for short periods of active time with the total duration of under 6 minutes (for example going to the toilet) (van der Berg et al. 2016). All bedtimes and arising times, derived by applying the modified algorithm, were visually confirmed. Bed- and arising times deemed invalid based on visual inspection were excluded from the further analyses. Postural transitions and movement during time in bed were then identified, and were categorized as activity during time in bed.

Regularity of time in bed patterns was studied based on determined bed- and arising times by using the Sleep Regularity Index (SRI), where higher scores indicate more regular patterns. The index describes the probability of being at the same state (asleep, awake) on any given time-points that are 24 hours apart (Phillips et al. 2017). Consistent with earlier reports (Phillips et al. 2017; Lunsford-Avery et al. 2018), SRI scores were categorized into quintiles, where the 1st quintile represents those with irregular time in bed and the 5th quintile those with regular time in bed. Those with intermediate regularity of time in bed (2nd, 3rd, and 4th quintile) were also included in the analyses. Similarly, to identify those with early and late bedtimes and arising times, mean bedtimes and arising times were divided into quintiles, and categorized these into early (1st quintile), intermediate (2nd, 3rd, and 4th quintile) and late (5th quintile).

4.3.3 Self-reported physical activity and neighborhood mobility

In the LISPE study (Study V), self-reported physical activity level was assessed at baseline and at one-year follow-up with a modified version of a single-item scale (Grimby 1986) which takes into account the frequency and intensity of habitual physical activity. The scale has seven response options ranging from mostly resting to engaging in competitive sports. For further analyses, the response options were categorized into low activity (at most light physical activity), moderate activity (at most three hours per week of moderate activity) and high physical activity (at least four hours of moderate activity per week). The modified version of the scale with the three-point response scale has been validated and found to correlate well with accelerometer-based physical activity measures (Portegijs et al. 2016). In LISPE, the self-reported physical activity scale was also used to assess reduction in physical activity between baseline and the one-year follow-up. Participants who reported a lower level of physical activity at follow-up were considered to have a reduced level of physical activity. For further analyses, participants were categorized into those who had and those who had not reduced their physical activity level over the follow-up period. In AGNES, a similar modified version of the single-item scale and the Yale Physical Activity Survey (Dipietro et al. 1993) were used to assess self-reported physical activity.

In LISPE, physical activity was additionally assessed as frequency of neighborhood mobility at baseline and at the one-year follow up. Neighborhood mobility was assessed with a single item from the University of Alabama at Birmingham Study of Aging Life-Space Assessment questionnaire (Baker, Bodner & Allman 2003). Participants reported how often they had been out into their neighborhood (other than own yard or apartment building) during the preceding four weeks. The response options were “daily”, “4-6 times per week”, “1-3 times per week” and “less than weekly”. Responses were subsequently recoded into “3 times per week or less”, “4-6 times per week” and “daily” for further analyses. In addition, reduced neighborhood mobility was assessed at baseline and at the one-year follow-up. Participants who reported less frequent neighborhood mobility at the one-year follow-up than at baseline were considered to have reduced their level of neighborhood mobility (vs. those who had not).

4.3.4 Accelerometer-based physical activity

In addition to self-reported measures, physical activity was assessed with accelerometers. In LISPE (Study V), a subgroup (n=174) of participants wore an accelerometer (Hookie AM20 Activity Meter, Hookie Technologies Ltd, Espoo, Finland) on their right hip for seven consecutive days after a baseline interview. The accelerometer was used during waking hours except when bathing or engaging in activities that could result in the device being exposed to water and was removed during the night. During the measurement period, participants were encouraged to continue their normal daily routines. In addition, they were instructed to fill in a daily activity diary in which they reported their accelerometer wear time, including any breaks during the day (Rantanen et al. 2012). Days with at least 10 hours of wear time were considered valid. Daily physical activity was assessed as daily mean step counts. Step counts were calculated from the accelerometer recordings using the manufacturer’s default settings for thresholds and formulas. Participants with at least four valid measurement days were included in the analyses.

In AGNES, participants wore two (trunk and thigh-worn) accelerometers consecutively for three to seven days following a home interview (Studies II and III). The accelerometers were attached using waterproof film and not removed during the measurement period. The battery on the trunk-worn device lasted about four days and was replaced with a new device by the research staff in the participant's home. Participants were instructed to avoid longer water-related activities, such as swimming, while wearing the accelerometers. They were also instructed to complete an activity diary in which they reported any breaks in wearing one or both accelerometers and any physical activities other than walking.

Recordings from both accelerometers were processed simultaneously. The resultant accelerations were calculated for the sampling instants and mean amplitude deviation (MAD) was calculated for all non-overlapping 5-s epochs (unpublished analysis). Waking hours were determined as the time between arising time and the following bedtime (van der Berg et al. 2016). For all valid waking hours, time spent in physical activity was calculated based on posture and signal intensities. Epochs spent in an upright posture and with MADs exceeding 0.035 g were categorized as walking or more vigorous physical activity. Furthermore, for both devices, all upright epochs below 0.035 g were categorized as standing activities. The threshold of 0.035 g was determined based on laboratory experimentation (Skantz et al. 2021).

4.3.5 Activity fragmentation

Activity fragmentation was calculated as the reciprocal of physical activity bout duration and derived from the accelerometer data of the AGNES study (Studies II and III). Only data from the thigh-worn accelerometer were used. Activity fragmentation was operationalized using two definitions: upright posture and MADs corresponding to at least 0.0167 g (Vähä-Ypyä et al. 2015). Posture categories were identified for each 5-second epoch and the median posture for each minute was used to calculate daily minutes spent in an upright posture. Mean minutes of daily active time and mean number of daily active bouts were calculated separately based on intensity and posture.

Activity fragmentation was calculated as the Active-to-Sedentary Transition Probability (ASTP) and was performed by dividing mean daily physical activity bouts by the mean sum of daily active minutes (Wanigatunga et al. 2018; Schrack et al. 2019). The results for the corresponding analyses are reported per 0.1-point increase in the ASTP measures. Higher values indicate higher activity fragmentation.

4.3.6 Unmet physical activity need

In the FITSA and LISPE studies (Studies IV, V and unpublished), unmet physical activity need was measured with two questions "Do you feel that you would have the opportunity to increase your level of outdoor physical activity if someone recommended you do so?" and "Would you like to increase your level of outdoor physical activity?" The response options for both questions were "yes" and "no". Those who reported that they would like to increase their outdoor physical activity but perceived no opportunity for it were considered to experience unmet physical activity need (Rantakokko et al. 2010).

In the LISPE study, questions on unmet physical activity need were asked at baseline and at the one- and two-year follow-ups. Those who reported unmet physical activity need at baseline were excluded from analyses in Study V. Those who did not report unmet physical activity need at baseline but did so at the one-year or two-year follow-up were considered as having developed unmet physical activity need.

In the AGNES study (unpublished analyses), unmet physical activity need was assessed with two questions, one on willingness to increase physical activity and the other on perceived opportunity for physical activity. Willingness to increase physical activity was assessed with the question "Would you like to increase your level of physical activity?". The response options were 1) "Yes, I would like to be very much more active than I currently am", 2) "Yes, I would like to be much more active than I currently am", 3) "Yes, I would like to be a bit more active than I currently am, and 4) "No, I would not like to be more active than I currently am". Perceived opportunities for physical activity was assessed with the question "How do you perceive your opportunities for physical activity?" The response options were 1) "very good", 2) "good", 3) "moderate", 4) "poor", and 5) "very poor/ not possible". Participants who reported moderate to poor opportunities for physical activity and willingness to be more physically active were considered to experience unmet physical activity need.

4.3.7 General fatigue

A general feeling of fatigue was measured in the FITSA study (Study IV) with a single questionnaire-based question. The question was "Do you feel tired in the daytime daily or nearly daily?" and the response options were "yes" and "no". Fatigue was used as a dichotomous variable in the analyses.

In addition, in the LISPE and AGNES studies, fatigue was measured with two items drawn from the CES-D scale (unpublished analyses). Participants were asked to respond to two statements about how they have felt during the past week. The statements were: "I feel that everything I did was an effort" and "I could not get going." The response options were "rarely or none of the time", "some or a little of the time", "occasionally or a moderate amount of the time", and "all of the time". Participants who selected occasionally or a moderate amount of the time or all of the time in response to either of the two statements were, in line with previous reports (Vestergaard et al. 2009), considered as fatigued.

4.3.8 Physical fatigability

In AGNES (Studies I, III and unpublished), physical fatigability in daily life was measured with the Physical Fatigue Subscale (PFS) of a Finnish version of the Situational Fatigue Scale (Yang & Wu 2005) during a home interview. The subscale consists of four activity items (e.g., taking a walk for an hour, cleaning the house for 30 minutes). Participants were asked to report on a six-point scale how fatigued they get after performing the given activity items. Response options ranged from "not fatigued at all" to "extremely fatigued". Participants scores for each activity item was then summed (range 0-20, higher scores indicating higher fatigability).

In AGNES (Studies I, III and unpublished), perceived exertion fatigability and performance fatigability severity were assessed during a modified 6-minute walk (6MWT) test that was conducted at the research center. Participants were asked to walk for six minutes at their usual preferred pace on an indoor corridor. The length of each lap taken was 40 meters. A walking aid was permitted during the 6MWT, if necessary. The participants were asked to rate their perceived exertion on the Borg Rating of Perceived Exertion Scale (Borg 1982) (RPE, range 6–20, 6 = no exertion and 20 = completely exhausted) before and after completing the 6MWT. In addition, lap times were recorded using accelerometers. Perceived exertion fatigability was assessed using a modified version of a previously validated method (Murphy, Kratz & Schepens Niemiec 2017). The score was calculated by dividing the RPE rating at the end of the 6MWT by the RPE rating at the beginning of the test. The resulting score was then further divided by meters walked during the 6MWT and multiplied by 1 000 for reporting purposes. Higher scores indicate higher perceived exertion fatigability.

In AGNES (Studies I, III and unpublished), the severity of performance fatigability was measured by assessing the proportion of the change in lap times relative to walking speed during the 6MWT. We assessed slowing between the second and the second-to-last lap to control for potential faster-than-average starting and anticipation of finish during the last lap (Simonsick et al. 2014). Performance fatigability severity was calculated using a modified version of a previously validated method (Schnelle et al. 2012; Murphy, Kratz & Schepens Niemiec 2017). The score was calculated by dividing the second-to-last lap time (s) by the second lap time (s) and, to account for walking speed, further dividing the product by the number of meters walked during the 6MWT. Finally, for reporting purposes, the resulting score was multiplied by 1 000. Higher scores indicate higher performance fatigability severity.

4.3.9 Mental fatigability

In AGNES (Study III and unpublished), mental fatigability in daily life was assessed with the Mental Fatigue Subscale (MFS) of the Situational Fatigue Scale. The scale consists of nine activity items (e.g., hosting a social event for 30 minutes, watching TV for two hours) and participants were asked to report on a six-point scale how fatigued they felt after performing each activity. Participants' scores were then summed for the analyses (range 0-45, higher scores indicating higher fatigability). Initial analyses showed that the scores on the scale were skewed towards zero, and hence the scores were categorized into quartiles.

In AGNES (Study III and unpublished), perceived mental fatigability was assessed as self-rated mental alertness both prior to and after the 6MWT. Participants were asked to report their level of mental alertness using a modified version of a 7-point Likert scale (1 = mentally exhausted and 7 = very alert and energetic) (Schnelle et al. 2012). For the analyses, participants were then dichotomized into those who experienced higher mental fatigue after the 6MWT and to those who experienced no change or felt more energetic.

4.3.10 Covariates and descriptive characteristics

Age was drawn from Digital and Population Data Services Agency in the context of participant recruitment and was used as a covariate in all analyses. Sex was also drawn from the population register and used as a covariate in the analyses utilizing data from the LISPE and AGNES studies. Years of education were assessed in the LISPE and AGNES studies and used as an indicator of socioeconomic status. In FITSA, socioeconomic status was assessed as perceived financial situation. Perceived financial situation was self-reported and dichotomized for the analyses as "very good or good" and "moderate, poor, or very poor."

The Short Physical Performance Battery (SPPB) (Guralnik et al. 1994) was used as a measure of lower extremity physical function, and used in Studies I, II, III and V, and in all additional analyses utilizing AGNES or LISPE data. In FITSA, mobility limitations were assessed as difficulty walking 2 km and used as a covariate in Study IV. For the analyses, the response alternatives were dichotomized as "no difficulties" (able to manage without difficulty) and "difficulties" (minor difficulties, major difficulties, I need help, or I am not able to). A similar question was used in AGNES to assess walking difficulties over 500 meters, and used in Study I. Morbidity was measured as number of chronic diseases and used in Studies I, III, IV, and V and additional unpublished analyses. In FITSA, number of chronic conditions was self-reported from a list of 22 common chronic conditions, and participants were asked to state for each condition whether it had been diagnosed by a physician or not. Participants were also asked to report any other physician-diagnosed chronic diseases. In LISPE, a list of 22 common chronic conditions was also used. In AGNES, a similar but longer list of 34 common chronic conditions was used. Depressive symptoms were assessed with the CES-D scale (Radloff 1977). For additional analyses that included the items on fatigue and restless sleep, the scale was dichotomized, using a previous approach, to avoid overlap (Gilbert et al. 2018). Any overlapping item was first removed and the scale then dichotomized into high depressive symptoms (≥16) or low depressive symptoms (<16) (Gilbert et al. 2018).

A modified self-report physical activity scale was used as a covariate in Study IV and in the analyses studying the associations between fatigability and unmet physical activity need (Grimby 1986). MAD or posture-based mean activity minutes were used as covariates in the studies that included the activity fragmentation measures (Studies II & III). Sleep medication use was asked with a single question in FITSA and used as a covariate in Study IV. Sleep medication use was also assessed in AGNES and derived from a self-reported list of medications (Study II). Accelerometer-based time in bed was used as a covariate in Study II.

4.4 Statistical methods

Data for Studies I, II, III and V and the additional analyses were performed using the IBM Statistical Package for Social Sciences (SPSS) version 24.0 for Windows. Data in Study IV were analyzed using Stata Statistical software Version 14 and IBM SPSS Statistics Version 24. In all analyses, the findings were considered as statistically significant when the p-value was <0.05 or the confidence intervals did not include 1.

4.4.1 Descriptive data

Descriptive information on participants were studied using means and standard deviations for continuous variables and percentages for categorical variables. Group differences between groups of three or more were studied using one-way analysis of variance (ANOVA) for normally distributed continuous variables and the Kruskal-Wallis test for non-normally distributed variables. Group differences between groups of two were tested with the Mann-Whitney U-test for continuous variables. For categorical variables, group differences were tested with chi-square tests. In Study IV, comparisons between groups were conducted with Wald tests adjusted for the interdependency within twin pairs. Correlations were tested with the Pearson correlation coefficient for normally distributed variables and Spearman's rank correlation coefficient for non-normally distributed or ordinal variables. In Study I, the initial validation for the modified performance fatigability scale was done with Spearman's rank correlation coefficients.

4.4.2 Regression analyses

In Study II, the associations of posture- and MAD-based activity fragmentation with habitual bedtimes, arising times and regularity of time in bed were analyzed using multinomial regression analyses. Associations of activity fragmentation measures with active bouts during time in bed and active minutes during time in bed were analyzed with linear regression analysis. Models were first adjusted for age and sex, after which education, depressive symptoms, cognitive function, and lower extremity function were added into the model. Finally, to see whether the associations were explained by differences in time in bed, we added mean time in bed in minutes into the models. All models were additionally adjusted for total activity minutes based on either posture or MADs to see whether total activity minutes explained the observed associations.

In Study III, linear regression analyses were used to study the association of posture- and MAD-based activity fragmentation with performance fatigability, perceived exertion fatigability, and physical fatigability in daily activities.

Preliminary analyses suggested that the distribution of the MFS was skewed towards zero, and therefore the scale was categorized into quartiles of mental fatigability for further analyses. The association of activity fragmentation and perceived mental fatigability after the 6MWT was studied using binary logistic regression analysis. Models were first adjusted for age and sex, and then for education, number of chronic conditions, lower extremity function, cognition, and depressive symptoms. All models were additionally adjusted for total activity minutes based on either posture or MADs to see whether total activity minutes explained the observed associations. Furthermore, activity-stratified analyses on the association of activity fragmentation with mental and physical activity were performed to see whether the associations were similar at all activity levels.

In Study IV, associations of daytime tiredness, perceived sleep quality, and sleep duration with unmet physical activity need were analyzed with binary logistic regression analyses. Models were first adjusted for age and then for chronic diseases, depressive symptoms, walking difficulties and physical activity. All models were additionally adjusted for dependency within the twin pairs.

In Study V, analyses between baseline physical activity level, frequency of neighborhood mobility, average step counts, and reductions in physical activity and neighborhood mobility with the development of unmet physical activity need over the follow-up period were studied with binary logistic regression analyses. Models were adjusted first for age and sex and then for SPPB score, CES-D score, number of chronic diseases and education. All the models that included accelerometer data were additionally adjusted for accelerometer wear time. Models that included reduction of physical activity or neighborhood mobility were additionally adjusted for baseline physical activity level or baseline frequency of neighborhood mobility.

Regarding the additional unpublished analyses, associations of the fatigability measures with unmet physical activity need were studied with binary logistic regression analysis. Models were adjusted first for age and sex and second, education, depressive symptoms, lower extremity physical performance, number of chronic conditions and self-reported physical activity were added into the models. Associations of restless sleep with unmet physical activity need were also studied with binary logistic regression analysis. The model was first adjusted for age and sex, after which perceived exertion fatigability, performance fatigability, PFS score, self-reported fatigue, high depressive symptoms, chronic conditions, SPPB score and MMSE score were added into the model one by one. Longitudinal associations of fatigue and restless sleep with the development of unmet physical activity need were studied with binary logistic regression analysis. Only those who did not report unmet physical activity need were included in the analyses. Model were first adjusted for age and sex, and then, education, SPPB score, chronic conditions, high depressive symptoms and MMSE score were added into the model. Finally, self-reported physical activity level was added into the model. The associations of unmet physical activity need and fatigue or restless sleep, with the development of fatigue and restless sleep were studied with a similar protocol.

4.4.3 Missing data

In Study III, missing data on fatigability on the SFS were imputed using the Multiple Imputation (MI) procedure in SPSS. Imputation was done due to the rather large proportion of missing data on some of the scale items. Of the participants, 114 (23%) had at least one missing item on the PFS subscale and 28 (6%) had at least one other missing item on the MFS subscale. Items with the most missing responses were perceived fatigue after jogging for 20 minutes (n = 107) or playing a ball game for 30 minutes (n = 89). Furthermore, non-drivers were not asked the question about perceived fatigability after driving for an hour (n = 128). Imputation was done based on responses to other items on the SFS, self-reported walking ability, modifications in climbing a flight of stairs, and walking distances of 2 km and 500 m, self-rated health, three instrumental activities of daily living, three items from the CES-D scale, and perception of sufficient health to go out and about. Furthermore, activity fragmentation was included in the imputation model because the addition of predictors in imputation models has been shown to lead to less biased estimates (Rubin 1996). Twenty datasets of imputed values were created, and pooled results were reported for the corresponding analyses.

In Study IV, missing observations in the explanatory variables (perceived sleep quality (n = 4), daytime tiredness (n = 6), and sleep duration (n = 3)) were imputed based on participants' earlier responses from the previous data collection wave.

5 RESULTS

5.1 Characteristics of participants

Participant characteristics in AGNES, LISPE and FITSA projects and the subsamples included in the present analyses are summarized in Table 1.

TABLE 1 Characteristics of participants in the datasets used in this study

	AGNES total n=1021	AGNES PA n=485	FITSA total n=344	FITSA n=302	LISPE total n=848	LISPE n=700	LISPE PA n=156
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Age, years	78.8 ± 3.6	78.4 ± 3.4	79.1 ± 3.3	79.0 ± 3.3	80.6 ± 4.2	80.3 ± 4.2	80.2 ± 4.2
Education, years	11.5 ± 4.2	11.6 ± 4.3	-	-	9.6 ± 4.1	9.7 ± 4.2	9.8 ± 4.1
SPPB score	9.9 ± 2.4	10.3 ± 1.9	-	-	9.6 ± 2.5	9.9 ± 2.2	10.4 ± 1.8
CES-D score	8.6 ± 7.1	7.8 ± 6.6	14.1 ± 7.7	14.2 ± 7.8	9.6 ± 6.8	9.2 ± 6.6	9.2 ± 6.4
MMSE score	27.1 ± 2.6	27.4 ± 2.4	-	-	26.1 ± 2.8	26.2 ± 2.7	26.5 ± 2.6
Number of chronic conditions	3.4 ± 2.0	3.3 ± 2.0	3.9 ± 2.4	4.0 ± 2.4	4.4 ± 2.4	4.2 ± 2.4	4.2 ± 2.3
	%	%	%	%	%	%	%
Women	57.2	59.7	100.0	100.0	62.0	60.4	62.2
WD 2 km	36.2	29.0	59.1	59.1	42.0	35.5	27.6

PA=Physical activity, SPPB=Short Physical Performance Battery, CES-D=Center for Epidemiologic Studies Depression Scale, MMSE=Mini Mental State Examination, WD=Walking difficulties

5.2 Accelerometer-based physical activity, sedentary behavior and time in bed during continuous 24-hour physical activity monitoring

On average, the participants spent 14.1% (95% CI 12.9-15.3) of their waking hours lying down, 48.7% (95% CI 47.4-50.1) sitting, 26.0% (95% CI 25.0-27.0) in standing activities and light movement and 11.2% (95% CI 10.7-11.7) in walking and more vigorous activities (Figure 4). Statistically significant age-related differences were observed only in the proportion of time spent in walking and more vigorous activities, which was slightly lower in the oldest age group (75-year-olds 11.5%, 95% CI 10.8-12.1, 80-year-olds 11.5%, 95% CI 10.4-12.6, 85-year-olds 9.0%, 95% CI 7.7-10.3 of waking hours).

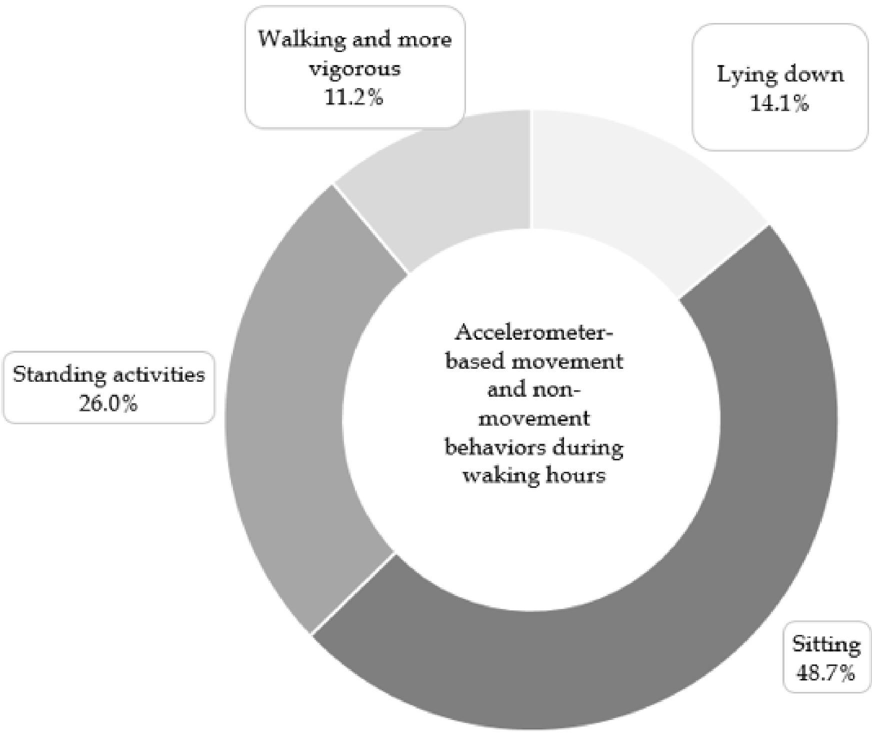

FIGURE 4 Accelerometer-based physical activity and sedentary behavior as proportions of waking hours among participants in the AGNES physical activity surveillance.

During a 24-hour period, the participants spent an average of 8.4% (95% CI 7.7-9.1) of the time lying down in the daytime, 29.1% (95% CI 28.2-30.0) sitting, 15.4% (95% CI 14.8-16.1) in standing activities and light movement, 6.6% (95% CI 6.3-7.0) walking and in more vigorous activities and 37.3% (95% CI 36.8-37.7) in bed (Figure 5). As in waking hours, age-related differences were only observed in the proportion of time spent in walking and more vigorous activities, which slightly decreased among the oldest age group (75-year-olds 6.8%, 95% CI 6.4-7.2, 80-year-olds 6.9%, 95% CI 6.2-7.5, 85-year-olds 5.2%, 95% CI 4.5-5.9).

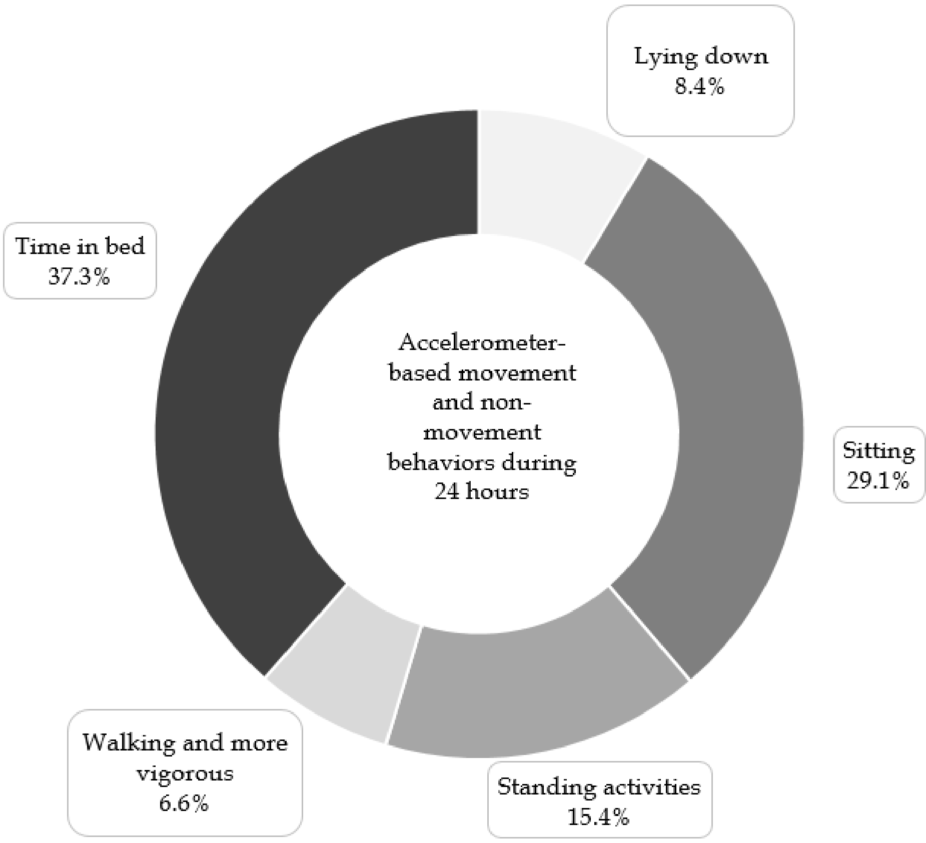

FIGURE 5 Accelerometer-based physical activity, sedentary behavior, and time in bed during 24 hours among participants in the AGNES physical activity surveillance.

The correlation between posture- and MAD-based activity fragmentation was moderate (Spearman's rho = .39, $p < 0.001$). Figure 6 shows an example of how posture-based activity fragmentation was manifested in the daily accelerometer data. On average, those with higher posture-based activity fragmentation accumulated less physical activity, and their physical activity accrued in shorter activity bouts, compared to those with lower activity fragmentation ($p<0.001$ for all). The results were similar for intensity-based physical activity fragmentation.

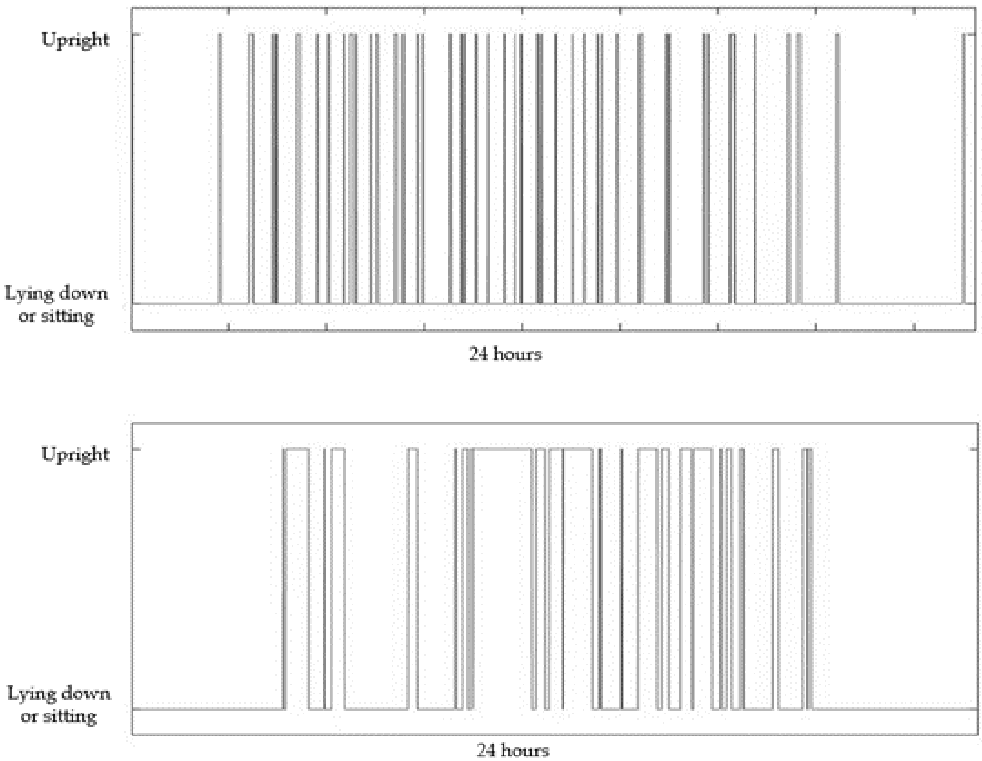

FIGURE 6 Examples of daily physical activity patterns based on posture-based fragmentation; A) 24-hour posture-based activity accumulation of a person with high posture-based fragmentation: activity is accumulated in shorter bouts and total activity minutes are lower. B) 24-hour posture-based activity accumulation of a person with low posture-based physical activity fragmentation: activity is accumulated in both short and longer bouts and total activity minutes are higher.

5.3 Initial validation of the performance fatigability scale (Study I)

The correlations of the modified performance fatigability scale with fatigability, physical activity, physical function, and health variables are summarized in Table 2. The scale showed a relatively strong correlation with perceived exertion fatigability. Correlations with self-reported fatigability measures were moderate. The performance fatigability scale, in particular, was strongly negatively correlated with gait speed. Correlations with self-reported physical activity, SPPB, age, and chronic conditions were from weak to moderate and in the expected directions.

TABLE 2 Spearman correlation coefficients of performance fatigability with measures of fatigability, physical activity, and health (n = 778)

	PEF	SFS	PFS	Walking difficulty 500 m	Gait speed 10 m	SPPB	YPAS	Age	Number of chronic conditions
Performance fatigability	0.67	0.42	0.49	0.49	-0.79	-0.56	-0.41	0.31	0.30

p<0.001 for all; PEF= Perceived exertion fatigability; SFS= Situational Fatigue Scale total score; PFS=Physical Fatigue Subscale; SPPB=Short Physical Performance Battery; YPAS=Yale Physical Activity Survey

5.4 Associations of activity fragmentation with sleep-related characteristics and fatigability (Studies II & III)

The associations of activity fragmentation and total physical activity with sleep-related characteristics were studied in Study II. Associations of activity fragmentation with physical and mental fatigability were studied in Study III.

TABLE 3 Results of the linear regression analyses of the associations of physical activity fragmentation with sleep-related characteristics and the physical fatigability measures

	B	SE	p
Active minutes during TIB[a]			
MAD-ASTP	5.08	1.14	<0.001
Posture-ASTP	5.72	1.28	<0.001
TIB[b]			
MAD-ASTP	-35.73	8.32	<0.001
Posture-ASTP	-13.87	9.42	0.142
Physical fatigability in daily life[b]			
MAD-ASTP	0.92	0.46	0.046
Posture-ASTP	1.53	0.52	0.003
Performance fatigability[b]			
MAD-ASTP	0.16	0.06	0.004
Posture-ASTP	0.37	0.07	<0.001
Perceived exertion fatigability[b]			
MAD-ASTP	0.43	0.13	0.001
Posture-ASTP	0.66	0.16	<0.001

TIB=time in bed; MAD-ASTP= Active-to-Sedentary Transition Probability based on Mean Amplitude Deviation; Posture-ASTP= Active-to-Sedentary Transition Probability based on posture; [a]adjusted for age, sex, depressive symptoms, cognitive function, lower extremity physical performance, total activity minutes and time in bed; [b]adjusted for age, sex, education, depressive symptoms, cognitive function, lower extremity physical performance and total activity minutes

The linear regression analyses revealed that both higher posture-based and intensity-based activity fragmentation were associated with higher active minutes during time in bed. Higher intensity-based ASTP was associated with shorter time in bed only after adding total activity minutes into the model. In contrast, posture-based ASTP was no longer associated with TIB after adjusting for total activity minutes. Both ASTP measures were associated with all the physical fatigability measures, including higher performance fatigability, higher perceived exertion fatigability and higher self-reported physical fatigability in daily activities. These associations were attenuated, but remained statistically significant, after adjusting for age, sex, education, lower extremity function, cognition, depressive symptoms, and total minutes spent in at least light intensity physical activity (Table 3). The associations of posture- and intensity-based activity fragmentation with performance fatigability were similar in the most active tertile.

TABLE 4 The associations of physical activity fragmentation with sleep-related characteristics and the mental fatigability measures

	OR (95% CI)	OR (95% CI)
Regularity of TIB[a]	Intermediate TIB	Irregular TIB
MAD-ASTP	1.05 (0.50-2.19)	1.36 (0.57-3.27)
Posture-ASTP	2.91 (0.94-9.06)	3.67 (1.04-13.00)
Bedtime[a]	Early quintile	Late quintile
MAD-ASTP	0.70 (0.31-1.57)	2.15 (0.95-4.86)
Posture-ASTP	1.28 (0.58-2.84)	1.09 (0.41-2.92)
Arising time[a]	Early quintile	Late quintile
MAD-ASTP	0.56 (0.25-1.25)	0.99 (0.46-2.13)
Posture-ASTP	1.63 (0.71-3.78)	0.91 (0.40-2.06)
Perceived mental fatigability after 6MWT[b]	Higher mental fatigability after 6MWT	
MAD-ASTP	0.88 (0.52-1.48)	
Posture-ASTP	1.79 (0.94-3.20)	
Mental fatigability quartiles[b]	Higher mental fatigability	
MAD-ASTP	0.92 (0.59-1.42)	
Posture-ASTP	1.12 (0.68-1.86)	
General fatigue[b]	Fatigued	
MAD-ASTP	1.95 (0.82-4.63)	
Posture-ASTP	1.66 (0.64-4.34)	

TIB=time in bed; MAD-ASTP= Active-to-Sedentary Transition Probability based on Mean Amplitude Deviation; Posture-ASTP= Active-to-Sedentary Transition Probability based on posture; 6MWT=six-minute walking test; [a]adjusted for age, sex, depressive symptoms, cognitive function, lower extremity physical performance, total activity minutes and time in bed; [b]adjusted for age, sex, education, depressive symptoms, cognitive function, lower extremity physical performance and total activity minutes

The multinomial regression analyses revealed that higher posture-based ASTP was associated with higher odds for an irregular compared to regular pattern of time in bed. Higher intensity-based ASTP was associated with higher odds for a late bedtime compared to intermediate bedtime, but this association was attenuated after adjusting for time in bed and total activity minutes. No other statistically significant associations were found between the ASTP measures and the timing and variability of time in bed (Table 4).

With respect to the measures of mental fatigability, 33% of the participants experienced more mental fatigue after than before the 6MWT. The binary logistic regression analyses revealed that higher posture-based activity fragmentation was associated with higher perceived mental fatigability after the 6MWT in the age- and sex-adjusted models. However, the association was attenuated and lost statistical significance after other covariates were added into the models. The ordinal regression analyses revealed that higher scores in both the ASTP measures were associated with higher self-reported mental fatigability in daily activities when adjusted for age and sex but also that both associations were attenuated after adding other covariates into the models. Higher scores in both the intensity- based and posture-based ASTP scales were associated with two-fold higher odds for general fatigue in the unadjusted model. However, when adjusted for total activity minutes, the model explained both associations.

5.5 Associations of sleep characteristics and fatigability with unmet physical activity need (study IV and unpublished data)

The logistic regression analyses among the participants of the FITSA study revealed that participants with short habitual sleep duration had nearly five-fold higher odds for unmet physical activity need compared to those with normative sleep duration, when adjusting only for age. Adjusting for health-related variables attenuated the odds to three-fold, but the association remained statistically significant. Long sleepers had three-fold higher odds for unmet physical activity need in the age-adjusted models, but the association did not reach statistical significance. No statistically significant association was observed between perceived sleep quality and unmet physical activity need. Poor perceived sleep quality was not associated with unmet physical activity need (Table 5).

TABLE 5 Cross-sectional associations of sleep characteristics, fatigue and fatigability with unmet physical activity need in the FITSA and AGNES studies

	Model 1	Model 2
	OR (95% CI)	OR (95% CI)
Sleep duration[a]		
<6 hours vs. 6-8 hours	4.62 (1.95-10.98)	3.23 (1.21-8.65)
>8 hours vs. 6-8 hours	2.96 (0.88-9.90)	2.70 (0.74-9.81)
Poor perceived sleep quality vs. good[a]	1.95 (0.88-4.32)	1.44 (0.55-3.77)
Fatigued vs. no[a]	2.25 (1.04-4.85)	0.87 (0.38-2.01)
Performance fatigability[b]	3.64 (2.62-5.05)	2.26 (1.48-3.43)
Perceived exertion fatigability[b]	1.80 (1.48-2.18)	1.32 (1.05-1.67)
Physical fatigability in daily life[b]	1.20 (1.14-1.27)	1.07 (1.01-1.14)
Mental fatigability after 6MWT[b]	1.70 (1.19-2.43)	1.19 (0.79-1.79)

6MWT=six-minute walking test, [a]Data from the FITSA study used, [b]Data from the AGNES study used, [a]Model 1 age-adjusted, Model 2 adjusted for age, depressive symptoms, chronic conditions, walking difficulties and self-reported physical activity; [b]Model 1 adjusted for age and sex, Model 2 adjusted for age, sex, education, depressive symptoms, physical performance, chronic conditions and self-reported physical activity

Participants who reported fatigue had two-fold higher age-adjusted odds for unmet physical activity need, compared to those who did not report fatigue, but this association was explained by higher prevalence of diseases, depressive symptoms, and walking difficulties among those experiencing fatigue symptoms and unmet physical activity need. In the AGNES study, performance fatigability, perceived exertion fatigability and physical fatigability in daily life all increased the odds for unmet physical activity need, and the association remained statistically significant even after adjusting for education, depressive symptoms, physical performance, chronic conditions, and self-reported physical activity. Higher mental fatigability increased the odds for unmet physical activity need, but the association was attenuated in the fully adjusted model (Table 5).

TABLE 6 Associations of restless sleep with unmet physical activity need in the AGNES study (n = 776)

	Unmet physical activity need vs. no
	OR (95% CI)
Age and sex	1.69 (1.14-2.52)
+ Perceived exertion fatigability	1.51 (0.99-2.29)
+ Performance fatigability	1.31 (0.82-2.08)
+ PFS	1.39 (0.85-2.27)
+ General fatigue	1.66 (1.15-2.41)
+ High depressive symptoms	1.55 (1.07-2.26)
+ Chronic conditions	1.67 (1.14-2.45)
+ SPPB	1.62 (1.11-2.36)
+ MMSE	1.79 (1.24-2.57)

PFS=Physical Fatigue subscale; SPPB=Short Physical Performance Battery; MMSE=Mini Mental State Examination

To see whether higher fatigability levels explained the association between sleep and unmet physical activity need, additional analyses were run on the AGNES study participants. Logistic regression analyses showed that restless sleep increased the odds for unmet physical activity need in the age- and sex-adjusted model. The association was attenuated the most when the fatigability measures were added into the model (Table 6). Finally, to see whether fatigue and restless sleep preceded the development on unmet physical activity need over time, and vice versa, additional analyses were performed on the LISPE data. Logistic regression analyses showed that while fatigue increased the odds for the development of unmet physical activity need over the follow-up period, the association was explained by lower physical activity level. Reporting restless sleep at baseline was not associated with the development of unmet physical activity need. Unmet physical activity need predicted the development of fatigue over the follow-up, but this association was also explained by physical activity level. Reporting restless sleep at baseline predicted fatigue over time, and the association remained statistically significant even after adjusting for education, SPPB, chronic conditions, high depressive symptoms, MMSE and physical activity level. However, neither unmet physical activity need or fatigue were not associated with the development of restless sleep over the follow-up period (Table 7).

TABLE 7 Longitudinal associations between unmet physical activity need, fatigue, and restless sleep in the LISPE study

	Model 1	Model 2	Model 3
	OR (95% CI)	OR (95% CI)	OR (95% CI)
	Development of unmet physical activity need (n=700)		
Fatigue	2.32 (1.39-3.87)	1.04 (0.56-1.94)	0.99 (0.54-1.83)
Restless sleep	1.11 (0.65-1.89)	0.73 (0.40-1.35)	0.79 (0.43-1.46)
	Development of fatigue (n=597)		
Unmet physical activity need	2.08 (1.12-3.88)	2.08 (1.06-4.07)	1.87 (0.95-3.68)
Restless sleep	3.14 (1.83-5.37)	1.99 (1.08-3.66)	2.10 (1.13-3.88)
	Development of restless sleep (n=584)		
Unmet physical activity need	0.86 (0.39-1.91)	0.71 (0.31-1.62)	0.70 (0.31-1.61)
Fatigue	1.29 (0.62-2.69)	0.74 (0.30-1.81)	0.74 (0.30-1.81)

Model 1 adjusted for age and sex; Model 2 adjusted for education, physical performance, chronic conditions, high depressive symptoms, cognitive function; Model 3 adjusted for same variables as Model 2 + self-reported physical activity level

5.6 Associations of activity fragmentation and physical activity with unmet physical activity need (study V and unpublished data)

Study V investigated the longitudinal associations of physical activity level and neighborhood mobility with the development of unmet physical activity need. To see whether activity fragmentation was associated with unmet physical activity need cross-sectionally, additional unpublished analyses were performed.

Cross-sectional logistic regression analyses among the AGNES participants showed that posture-based activity fragmentation increased the odds for unmet physical activity need when adjusted for age and sex (OR 2.67, 95% CI 1.70-4.20, per 0.1-point increase). The association was attenuated after adjusting for cognitive function, physical performance, depressive symptoms, chronic diseases, education, and total activity minutes. The association was mostly explained by differences in physical performance and total activity minutes. The results for intensity-based activity fragmentation were similar. Higher intensity-based ASTP scores increased the odds for unmet physical activity need (OR 1.96, 95% CI 1.33-2.90), but the association was attenuated in the fully adjusted model. The association was mainly explained by lower total activity minutes, poorer physical performance, and having more chronic conditions.

The results of the longitudinal analyses among the LISPE participants are summarized in Table 8. The findings revealed that a low level of physical activity predicted the development of unmet physical activity need over the two-year follow-up, even after adjusting for several health-related factors. While going outdoors into the neighborhood three times per week or less predicted the development of new unmet physical activity need, this association was explained by poorer overall health among those with the lowest frequency of neighborhood mobility. Higher baseline step counts reduced the odds for unmet physical activity need over the two-year follow-up. Furthermore, reductions in physical activity level and the frequency of neighborhood mobility both resulted in increased odds for the development of unmet physical activity need.

TABLE 8 Associations between physical activity, neighborhood mobility and the development of unmet physical activity need

	Development of unmet physical activity need (n= 700)	
	Model 1	Model 2
	OR (95% CI)	OR (95% CI)
Physical activity level		
Moderate vs. high	1.89 (1.10-3.23)	1.62 (0.93-2.82)
Low vs. high	4.37 (2.62-7.29)	2.41 (1.38-4.21)
Frequency of neighborhood mobility		
4-6 times/week vs. daily	1.67 (1.05-2.65)	1.42 (0.87-2.31)
3 times/week or less vs. daily	3.02 (1.86-4.90)	1.67 (0.98-2.85)
Reduction in physical activity vs. no[a]	3.10 (1.79-5.34)	2.57 (1.46-4.51)
Reduced frequency of neighborhood mobility vs. no[a]	2.06 (1.31-3.24)	1.95 (1.21-3.15)
	Development of unmet physical activity need (n=152)	
Average step count[b] per 1000 steps	0.68 (0.54-0.87)	0.74 (0.58-0.95)

Model 1 adjusted for age and sex; Model 2 adjusted for age, sex, physical function, depressive symptoms, number of chronic diseases and years of education; [a]adjusted additionally for baseline physical activity level or frequency of neighborhood mobility; [b]adjusted additionally for accelerometer wear time

6 DISCUSSION

This study showed that older people with poorer sleep characteristics and higher physical fatigability may be at higher risk for unmet physical activity need in old age. The relationship between poorer sleep and unmet physical activity need may be partly explained by higher fatigability, an observation that should be confirmed in future studies. Older people with high levels of fatigue and co-occurring comorbidities may be unable to participate in physical activity sufficiently, leading them to experience unmet physical activity need. This study also shed light on the importance of the patterns of accumulating physical activity in old age.

This research expanded knowledge on the relationships between sleep, fatigue, and physical activity in old age by showing that sleep characteristics and fatigability were associated with fragmented activity patterns and unmet physical activity need. The study concepts constitute an entity comprising the themes of rest, fatigue and activity in the lives of older people and lay a foundation for future research and interventions aiming at promoting physical activity among individuals who lack the opportunity to increase their physical activity unaided.

6.1 Associations of physical activity fragmentation with sleep characteristics and fatigability

This study showed that higher activity fragmentation was associated with higher physical fatigability and poorer sleep-related characteristics, namely more active time during time in bed, shorter time in bed and irregular patterns of time in bed. However, in the adjusted models, activity fragmentation was not associated with higher mental fatigability.

The accumulation of daily physical activity in a more fragmented manner may reflect pacing behavior during activities, one of the frequently used adaptive strategies to alleviate activity-related fatigue (Eldadah 2010). Daily physical activities, such as walking, may become increasingly energetically demanding with advancing age and multiplying underlying comorbidities (Schrack et al. 2012). Activities that approach the maximum energetic limit, irrespective of its magnitude, will likely lead to fatigue (Alexander et al. 2010). Taking breaks allows people to reduce the task demands, thereby conserving energy. Avoiding longer continuous bouts of physical activity to alleviate activity-related fatigue may allow older people to engage in physical activities and accumulate a relatively high daily amount of physical activity. Although those with higher activity fragmentation were more likely to have a lower volume of total physical activity, the association between activity fragmentation and higher physical fatigability was not limited to those with low physical activity but was also evident among those whose volume of physical activity was relatively high. These findings were in line with an earlier study and support the hypothesis that activity fragmentation is an early sign of higher fatigability and impending functional decline (Schrack et al 2019). Identifying individuals at risk for impending high fatigability is important for preventing the consequences that fatigability has on daily activities and to prevent further increase in fatigability.

Poor and nonrestorative sleep may exacerbate fatigue related to daily activities and be one of the factors underlying higher fatigability (Aldughmi et al. 2016; Kratz et al. 2019; Alfini et al. 2020). This may result in an increased need to pace daily physical activity. Although our use of thigh- and trunk-worn accelerometers did not allow us to assess sleep per se, time in bed, bedtime and arising times describe behavioral aspects of sleep. Older persons with greater variability in sleep timing may also be less likely to achieve sufficient sleep (Paterson, Reynolds & Dawson 2018). Inappropriate sleep timing is also considered as a type of sleep deficiency, while spending more time in active behaviors during time in bed may also indicate more disturbed sleep. Moreover, engaging in shorter physical activity bouts may not be sufficient to achieve the beneficial effect of physical activity on sleep (Kredlow et al. 2015) and hence more fragmented activity patterns may also lead to poorer sleep characteristics and non-optimal sleep-related behavior. We did not assess interdaily variability in physical activity accumulation, but more fragmented activity patterns may also reflect a less regular pattern of physical activity. Regularity in daily routines may be associated with better sleep characteristics among older people (Zisberg, Gur-Yaish & Shochat 2010). Furthermore, short physical activity bouts are more likely to be accumulated indoors, where a person is less likely to encounter natural light. Photic cues are major pacers of the circadian rhythm of sleep and wake, and outdoor physical activity may help in synchronizing the rhythm with the 24-hour day.

Although higher activity fragmentation was not associated with higher mental fatigability in the adjusted models, one third of the participants felt mentally more fatigued after performing the 6MWT, which is predominantly a physical task. This indicates that feelings of fatigue can cross between its different dimensions and physical tasks can be considered as mentally fatiguing. This finding is in line with a recent conceptual model of fatigability (Kratz et al. 2019), and suggests that mental fatigue should also be considered when assessing factors that may hinder physical activity participation in old age. Activity fragmentation has been thought to be a function of higher age, fatigability and functional decline (Schrack et al. 2019; Wanigatunga, Ferrucci & Schrack 2019), and may provide a measure that can capture these changes at an early stage, allowing the initiation of preventive measures to postpone aging-related loss of resources.

6.2 Factors associated with unmet physical activity need

This dissertation research demonstrated that poorer sleep characteristics, higher fatigability and unmet physical activity need were associated among older people. The findings also showed that the development of unmet physical activity need was preceded by lower physical activity and neighborhood mobility levels and a recent reduction in physical activity. These findings provide information of value for physical activity promotion among older people with fatigue and poorer sleep characteristics.

Previous studies targeting physical activity and sleep have reported associations between poorer sleep and lower levels of physical activity. This study extends these previous findings by showing that self-reported short sleep duration also has independent associations with higher likelihood of unmet physical activity need. The present findings indicate that although insufficient sleep may reduce the opportunity for physical activity participation, the willingness to increase physical activity remains. A potential mechanism through which poor and insufficient sleep may affect physical activity participation is the experience of higher levels of fatigue (Holfeld & Ruthig 2014; Gilbert et al. 2018) or fatigability (Kratz et al. 2019). Although fatigue is a multifactorial symptom with several causes, sleep disturbances have been found to be one of the predictors of persistent fatigue, which in turn limits older people's participation in physical activity (Endeshaw 2015). Another previous study among a clinical sample of older adults found that poorer sleep characteristics were associated with higher perceived fatigability (Aldughmi et al. 2016). Similar associations were also quite recently found among relatively high-functioning older people (Alfini et al. 2020). The initial observation that the association between restless sleep and unmet physical activity need was attenuated after adjusting for physical fatigability suggests that fatigability may be one of the reasons explaining the association of poorer self-reported sleep and unmet physical activity need. Although these observations should be interpreted with caution, they do, however, suggest new hypothesis for testing in future studies, preferably in a longitudinal setting in which causal relationships between the phenomena can be investigated.

While the present findings revealed that general fatigue was associated with unmet physical activity need, this association was explained by poorer health status. The longitudinal analyses showed similar findings. Reporting fatigue at baseline was associated with the development of unmet physical activity need when adjusted only for age and sex; however, the association was attenuated when adjusted for health-related factors. Fatigue has been found to predict poorer physical function and disability (Avlund et al. 2002; Schultz-Larsen & Avlund 2007; Manty et al. 2015) and can therefore affect older people's ability to participate in physical activity, leading further to unmet physical activity need. Furthermore, because fatigue is associated with several diseases, both physiological and psychological (Avlund 2010), these conditions underlying tiredness may also lead to physical limitations and consequently hinder opportunities for physical activity participation. Poor health and mobility limitations have previously been found to be risk factors for unmet physical activity need (Eronen et al. 2014). Conversely, unmet physical activity need also preceded the development of high fatigue. This association was independent of baseline health status but explained by the lower physical activity levels of those experiencing unmet physical activity need. This finding resembles that of an earlier study showing that low levels of physical activity predict increased levels of fatigue (Martin et al. 2006). Finding ways to promote physical activity among those with unmet physical activity need could thus prevent further increase in fatigue and protect from its debilitating consequences.

One reason for the age-related decline in physical activity and the perception of unmet physical activity need in old age could be insufficient energy reserves for physical activities (Schrack, Simonsick & Ferrucci 2010; Schrager et al. 2014). Different factors, such as aging-related diseases and aging itself, influence how much energy a person has left over for physical activity during a day. Slower gait speed may be an adaptive strategy to compensate for the aging-related increase in the energetic cost of walking, as the energy cost of every meter walked increases with advancing age (Schrack et al. 2012). Therefore, the same distance to, for instance, the nearest shop may not only become energetically more demanding with normal aging but may also be related to the aging-related increase in disease burden and poor health and hence start causing fatigue. It has been hypothesized that energy regulation is one of the reasons underlying functional decline in old age (Schrack, Simonsick & Ferrucci 2010; Ferrucci et al. 2012). This is supported by a previous finding that an increase in the energetic cost of walking predicts gait speed decline over time (Schrack, Zipunnikov et al. 2016). Deveraux-Fitzgerald et al. found that for older people time and energy are valuable resources which they are not willing to squander (Devereux-Fitzgerald, Powell & French 2017). While the amount of physical activity perceived as sufficient is likely to vary between individuals, it has been suggested that movement is so essential for humans that the energy invested in these activities is only decreased when it is needed for other more vital activities (Schrack, Simonsick & Ferrucci 2010). Fatigability seems to be one manifestation of this aging-related energy depletion (Schrack et al. 2020). Whereas the associations of general fatigue coincided with poorer health and functioning among those with unmet physical activity need, the association between the measures of physical fatigability and unmet physical activity need remained even after adjusting for several health-related factors. Fatigability can be considered as an indicator of higher susceptibility to fatigue and likely to lead to adaptive behaviors aimed at avoiding activity-related fatigue, including a reduction in physical activity. Given their limited energy resources, people may be forced to prioritize and select the activities they feel will best repay the expenditure of their available energy. This, in turn, may mean that competing interests as barriers to physical activity are more likely to arise (Franco et al. 2015; Devereux-Fitzgerald, Powell & French 2017). In such instances, the desire to be more physically active is likely to remain, although opportunities for doing so may be perceived as poor or nonexistent.

Physical activity is important for many older people and is valued because it can help maintain health and independence (Franco et al. 2015). Physical activity can also contribute to the satisfaction of basic psychological needs (Springer, Lamborn & Pollard 2013). In the present study, lower levels of physical activity and lower frequency of neighborhood mobility preceded the development of unmet physical activity need over time. This finding is in line with other studies reporting cross-sectional associations between lower physical activity levels and unmet physical activity need (Eronen et al. 2012; Gao et al. 2020). Recently, Gao and colleagues found that older people experiencing unmet physical activity need accumulated less moderate-to-vigorous physical activity, especially during weekdays (Gao et al. 2020). The association between lower frequency of neighborhood mobility and the development of unmet physical activity need was explained by poorer health status. Consistent with findings of an earlier study (Rantakokko et al 2010), the reduction in the level of physical activity often preceded the development of unmet physical activity need. As physical activity (Paterson & Warburton 2010) and going outdoors daily (Jacobs et al. 2008) reduce the risk for mobility limitations in old age, lower levels of physical activity can accelerate decline in physical function, which is known to increase the risk for unmet physical activity need (Eronen et al. 2014). Going outdoors is, in many cases, a prerequisite for participation in several forms of physical activity and many older people accumulate physical activity while participating in activities that require going outdoors, which include activities such as walking for exercise and shopping (Tsai et al. 2016). Furthermore, older people who are physically less active and go out less frequently may not be aware of their opportunities for physical activity and thus may be more likely to stay indoors as their health declines. Adopting strategies that allow activities to continue may help older people maintain outdoor mobility and prevent unmet physical activity need for a longer period, whereas avoiding activities may lead to an accelerated decline in outdoor mobility and increase the risk for unmet physical activity need (Skantz et al. 2019). Pacing activities by taking breaks, which may be seen as fragmented activity patterns, is one of the strategies which reduce task demand and thus enable the continuance of engagement in physical activity (Skantz et al. 2019). The present study showed that higher activity fragmentation was cross-sectionally associated with unmet physical activity need only before adjusting for physical activity level. This finding indicates that activity fragmentation may be associated with unmet physical activity need only when coincident with low physical activity levels.

In old age, reducing participation in physical activity is often not a person's own choice but the result of different barriers to physical activity participation. Good health and the absence of severe mobility limitations are some of the prerequisites for independent physical activity participation. Good health is also an important determinant of physical activity initiation and maintenance (van Stralen et al. 2009) and thus older people with better health are more likely to have goals related to physical activities (Saajanaho, Rantakokko et al. 2016). Especially when they face mobility limitations, people are more likely to disengage from exercise-related goals and less likely to engage in new ones (Saajanaho, Viljanen et al. 2016). Poor health and mobility limitations are commonly reported barriers to physical activity (Cohen-Mansfield, Marx & Guralnik 2003; Rasinaho et al. 2007) and are known to increase the risk for unmet physical activity need (Eronen et al. 2012). As previously suggested, unmet physical activity need may be a transient phenomenon that is experienced after a reduction in habitual physical activity level (Rantakokko et al. 2010). If opportunities for physical activity participation are not improved, people may adapt to lower physical activity levels and their desire to be more physically active diminish.

While different barriers to physical activity may decrease the opportunities for physical activity participation, the willingness to increase physical activity is an important aspect of unmet physical activity need. Perception of unmet basic needs may cause higher distress to those who are unwillingly left out of physical activity. Furthermore, to attain permanent change in health behavior, the individual's personal motivation for change may be one of the key determinants of success. Therefore, identifying those who are already keen to increase their physical activity, but lack the opportunity to do so, form an important target group for physical activity interventions. Unmet physical activity need may have various harmful consequences for older people. While the perception of unmet basic need may be harmful in itself, not being able to attain the health benefits of physical activity due to insufficient opportunities may lead to accelerated health decline. This study showed that those who experienced unmet physical activity need were at higher risk for incident fatigue over time, which was explained by lower physical activity levels. However, it can be hypothesized that unmet physical activity need does not affect only those who actively participate in physical activity. To some extent, physical activity, or mobility, is vital for participation in all valued out-of-home activities. Unmet physical activity need may emerge in different stages of reduced physical activity, depending on the individual's own goals and values. Those who have engaged in high levels of physical activity throughout their lives may experience unmet physical activity need at an earlier stage. Another person may perceive unmet physical activity need when fatigue or another barrier to physical activity hinders their opportunity to participate in other valued activities. These considerations suggest that research on the development of unmet physical activity need in relation to older people's personal goals may prove fruitful. A recent study explored the association of perceived opportunities for physical activity with the willingness to increase physical activity at different levels of physical activity. The findings showed that poorer perceived opportunities were associated with higher willingness to engage in physical activity among older people who were moderately active. In contrast, poorer perceived opportunities for physical activity were not associated with willingness among those with low physical activity (Aartolahti et al. 2021).

Overall, the findings of this study suggest that unmet physical activity need may be a manifestation of aging-related decline in energetic resources and health, seen as higher activity-related fatigue, poorer sleep and reduced levels of physical activity. Both poorer sleep and lower physical activity levels can increase the risk for higher fatigue (Hossain et al. 2005; Martin et al. 2006), which is known as a barrier to physical activity (Cohen-Mansfield, Marx & Guralnik 2003; Kowal & Fortier 2007). To alleviate fatigue, older people may adopt different adaptive strategies, such as taking breaks, slowing down, and avoiding activities. Alleviating high activity-related fatigue by reducing physical activity levels can lead to a negative cycle that further hinders opportunities for physical activity participation and leads to unmet physical activity need. The findings of this study, along with the findings of previous studies, suggest that activity fragmentation may be an early indicator of fatigability and consequently functional decline. Assessment of activity fragmentation may provide an important tool for identifying those at risk for poorer sleep and higher fatigability and their potentially detrimental consequences. This study strengthens fatigue as a debilitating symptom among older people that may limit their opportunities for physical activity participation. Although the association of general fatigue and unmet physical activity need was explained by health status, the association of physical fatigability and unmet physical activity need remained even after controlling for participants' health and functional status. Older people who experience unmet physical activity need form an important target group for physical activity promotion as they are motivated to increase their physical activity but need support in doing so. This study showed that poor sleep characteristics and physical fatigability are likely to decrease the opportunity for physical activity participation in old age, while the will to be more physically active remains.

6.3 Theoretical aspects

The important role of maintaining active engagement in valued activities to secure greater wellbeing in old age has been acknowledged ever since the activity theory (Havighurst 1961) gained momentum in the 1960s. Although activity in old age does not refer solely to physical activities, physical activity has an essential role in old age. The role of adaptation to compensate for age-related loss of resources has also been acknowledged in several theoretical efforts to explain activity participation in old age (Havighurst 1961; Atchley 1989; Baltes & Baltes 1990).

This dissertation drew on a few relatively new and not yet thoroughly studied concepts, namely unmet physical activity need, fatigability, and activity fragmentation. When I read through the literature on fatigability and activity fragmentation, it became apparent that both could be located on the disablement pathway in old age. Both fatigability and activity fragmentation have been thought to be early indicators of acceleration in the aging process, potentially leading eventually to functional limitations and disability. However, during this dissertation process I found two newer theoretical models, namely the extended model of aging energetics and the conceptual model of fatigability, that were able to explain how higher activity-related fatigue leads to adaptive strategies, such as taking breaks and reducing physical activity. The model of aging energetics by Schrack et al. (2010), complemented previous theories with the notion of energy availability and energy regulation as potential underlying contributors to age-related adaptation and the progression of disability. This model seemed to provide a plausible explanation on how higher susceptibility to fatigue could lead to adaptive behaviors aimed at maintaining fatigue at an acceptable level, and how these adaptive behaviors could eventually lead to mobility limitations and reduced opportunities for physical activity participation. The more recent conceptual model by Kratz et al. (2019) further explained how poor sleep quality, insufficient sleep or sleep disturbances could further increase susceptibility to fatigue related to daily activities, again leading to adaptive behaviors, reduced physical activity and further increases in fatigue.

In sum, these models together seemed to provide a reasonable explanation for the interrelationships found between physical activity, sleep, fatigability, adaptive strategies, and unmet physical activity need in old age. Furthermore, building the theoretical foundation on which to explain the findings by drawing on recent novel theoretical models seemed fitting. It should be noted, however, that these theories are not wholly new but share some similarities and overlaps with the earlier theories and theoretical models.

Finally, many theories have sought to explain the physical activity paradox: although the health benefits of physical activity are widely known, why is it that many people continue to choose a sedentary lifestyle? The concept of unmet physical activity need explains part of this paradox at older ages. While many older people are willing to increase their physical activity, they lack the opportunity to do so. Other theories explaining this paradox are the dual-process models of physical activity, which posit that people may have unconscious tendencies to choose a sedentary lifestyle that are constantly at odds with the conscious awareness of the importance of increasing their physical activity. One of the most recent approaches, the theory of energy cost minimization (TECM), posits that the avoidance of physical activity may be explained by an innate drive towards energy conservation. The theory also posits that energy can be spared when the reward for the exertion is high enough. People who are highly physically active are likely to perceive physical activity as rewarding in itself, while others may view physical activity differently. Older people often value physical activity because it helps them to maintain their participation in other valued activities as well as their overall health and independence.

6.4 Methodological considerations

This dissertation was based on data collected for three larger research projects: the FITSA, LISPE and AGNES studies. The LISPE and AGNES studies included subsamples of participants who agreed to wear accelerometers, thereby allowing accelerometer-based assessment of physical activity, activity patterns and sleep-related characteristics. The FITSA and LISPE datasets had already been finalized when I started out on my dissertation journey, whereas the AGNES data collection was just beginning. I was thus able to participate in the AGNES data collection from the pilot interviews in 2016 to the home interviews and health checkups at the research laboratory. The AGNES data was therefore more familiar to me when I began running the analyses for the present sub studies.

In the LISPE study, participants wore the accelerometers only during waking hours. In contrast, the AGNES participants wore the accelerometers continuously. This allowed me to study 24-hour activity patterns and patterns of nighttime rest among the participants. My initial hope was to be able to obtain information on participants' sleep from the continuous accelerometer data, but this proved not to be possible from the thigh- and trunk-worn accelerometer data. The accelerometer data nevertheless allowed study of sleep-related characteristics such as time in bed and nightly variations in time in bed.

A topic that requires further methodological consideration is the measurement of mental fatigability. Although this study did not find independent associations between mental fatigability, activity fragmentation and unmet physical activity need, it should be noted that the methods used to assess mental fatigability may not have been optimal. We observed that the participants of the AGNES study reported lower levels mental fatigability than younger individuals, aged 18 to 60 years, who participated in the SFS validation study (Yang & Wu 2005). Initially, due to the aging-related cognitive decline, we expected that demanding cognitive and social activities would become increasing fatiguing. Some of the items on the scale may have more relevance for people who are still in working life, as after retirement people may be less exposed to burdensome mental tasks, and hence may experience less mental fatigue (Kratz et al. 2019). Moreover, older people are likely to have gained more experience than younger ones in performing a diversity of mental tasks during their lives, a factor which can be expected to reduce task demand. Many of the pitfalls related to the SFS have been recognized. The Pittsburgh Fatigability Scale, for example, has been specifically developed for use with older adults and to overcome the drawbacks of the SFS (Glynn et al. 2015). However, whether the Pittsburgh Fatigability Scale is able to capture fatigue related to mental work continues to be debated (Burke et al. 2018). Thus, it seems that the measurement of mental fatigability in old age warrants further methodological development. Another interesting observation related to mental fatigability was that a third of the participants in Study III felt more mentally fatigued after than before the 6MWT, which is primarily considered a physical task. This finding supports the recent conceptual model of fatigability (Kratz et al. 2019), showing that feelings of fatigue can cross between different domains. Mental as well as physical fatigability should also receive more consideration in the context of physical activity participation in old age.

Whereas physical activity fragmentation has previously been studied only in relation to intensity-based categories, this study extended the assessment of activity fragmentation to include posture-based categories. These two assessment methods showed only a moderate correlation with each other, indicating that the measures describe different aspects of physical activity patterns. The associations of both measures with physical fatigability were, however, similar. Furthermore, both measures also showed similar associations with total physical activity minutes and physical activity bouts, with higher activity fragmentation scores on both scales were associated with lower activity minutes and shorter physical activity bouts. Thus, posture-based activity fragmentation shows promise as a method of assessing physical behavior in older people.

The strengths of this study include the use of relatively large population-based study samples. Moreover, continuous accelerometer data was obtained for from 3 to 7 days, which allowed controlling for day-to-day variation in physical behavior. The possibility to use self-report measures of physical activity and fatigability was also a strength of this study. The different assessment methods complemented each other and showed consistency in the analyses. A further strength of this study was the development of a modified version of the performance fatigability scale, which aimed to overcome the theoretical limitations of the earlier computational methods. Theoretically, the new computational method is in line with the definition of performance fatigability, and the initial validation seemed promising among older adults. Another benefit of the newer computational method was that fewer conversion steps are needed when lap times are used. Although Van Geel et al. (2019) state that a maximal walking test can be recommended when measuring performance fatigability, there are instances when a self-paced walking test is preferable. Using a self-paced test may better reflect daily life situations (Schnelle et al. 2012) and thus describe performance fatigability in daily life. The findings showed a strong negative correlation between performance fatigability and walking speed, with higher scores on the scale correlating with slower walking speed. Therefore, when measuring performance fatigability using a self-paced walking test, the score reflects not only slowing down but also an adaptive process that is closely related to higher fatigability, namely slow walking speed. Slow walking speed is an independent predictor of several severe adverse outcomes, such as disability onset and higher mortality risk, both devastating consequences that fatigue may eventually have in older people's lives. Short and more fragmented sleep was associated with slower gait speed in an earlier study (Goldman et al. 2007), a relationship that might be explained by higher fatigability. Although the initial validation shows promise, the strong negative correlation of performance fatigability test with walking speed also shows that controlling for task demand may not be optimal. The further development of performance fatigability measures among older people is needed to optimally account for task demand.

Most of the limitations of this study stem from the fact that the study questions were secondary analyses of three larger study projects. This means that the sample sizes or research methods were not optimized specifically for the aims of this study. For instance, we did not have optimal assessment methods for assessing sleep. Furthermore, especially in the FITSA data, the number of participants experiencing unmet physical activity need was low, a factor which limited the statistical analyses. These limitations warrant future studies to confirm the findings using more optimal assessment methods and a larger study sample. Moreover, the studies were mostly cross-sectional. A cross-sectional study setting is usually acceptable when exploring new hypotheses, as in the present case. However, a cross-sectional setting does not allow causal inferences to be made, and thus the findings of this study can be used to generate new hypotheses for testing in future longitudinal studies. Furthermore, three different accelerometers and placements were used in this study. It should be noted that physical activity monitoring using different accelerometers placement, devices and methods will not produce exactly similar results and thus, are not directly comparable (Schrack, Cooper et al. 2016). Moreover, to study activity fragmentation, an acceleration cut point, which was originally developed for a waist-worn device was used (Vähä-Ypyä et al. 2015). Accelerations on the thigh are generally higher than on the waist (Fortune, Lugade & Kaufman 2014), and therefore, the total amount of at least light physical activity may have been overestimated. Studying unmet physical activity need as a dichotomous variable also has limitations. First, those who do not report unmet physical activity need form a rather heterogeneous group, and second, the measure does not capture the severity of unmet physical activity need. Furthermore, all the analyses were based on observational data, which may be prone to chance, bias, or confounding factors (Maki et al. 2014). Finally, in most of the analyses, the level of significance was not corrected although multiple tests were performed. This should be considered as one of the limitations of this study as it may have increased the risk for type I error in the findings. However, while many of the methods for correcting the level of statistical significance are efficient in reducing the risk for type I error, they tend to reduce statistical power and may simultaneously increase the risk for type II error.

6.5 Implications and future directions

The study has some important implications. Firstly, this study strengthened previous knowledge on fatigue as a debilitating symptom that limits older people's physical activity participation. The findings show that it may be more meaningful to assess fatigue anchored to daily activities, as this may provide a better, and possibly earlier, view on how fatigue may limit activities of daily living. Furthermore, the associations found between short self-reported sleep and unmet physical activity need highlight the importance of taking potential sleep difficulties into account when developing interventions aiming at promoting physical activity among older people. Older people experiencing unmet physical activity need form an important target group for physical activity interventions, since they are already motivated to increase their physical activity but need support to be able to achieve this goal.

This dissertation generated hypotheses for investigation in future studies. For instance, the present findings were largely based on cross-sectional associations, and therefore the causality of the associations cannot be determined. Future studies focusing on unmet physical activity need could further focus on how higher physical fatigability and shorter sleep duration may predict unmet physical activity need over time. In addition, future studies should further target the consequences of unmet physical activity need. The harmful consequences of unmet basic needs have been addressed in previous studies in relation to income and housing (Blazer, Sachs-Ericsson & Hybels 2005, Sachs-Ericsson, Schatschneider & Blazer 2006; Blazer, Sachs-Ericsson & Hybels 2007). The findings of this study could also be utilized when planning interventions aiming to promote equal opportunities for physical activity participation in old age.

Furthermore, as shown in this study, activity fragmentation may be a more meaningful measure of physical activity among older people than total activity minutes when targeting health-related outcomes. Although the posture-based activity fragmentation measure appears promising, the differences between the two activity fragmentation measures merit study in the future. In addition, while higher activity fragmentation seems to be associated with several adverse health outcomes, the effect of short activity bouts in breaking up sedentary time has been shown to be beneficial in several studies (Diaz et al. 2017). Comparing these two aspects of activity bouts could provide valuable additional information on physical behavior in old age. In addition, due to the methodological challenges presented by measuring mental fatigability, future studies should further develop measures that can accurately assess mental fatigability among older people.

7 MAIN FINDINGS AND CONCLUSIONS

1. More fragmented physical activity patterns may be associated with higher physical fatigability and poorer sleep characteristics beyond total physical activity volume.
2. Poorer sleep characteristics and higher physical fatigability showed cross-sectional associations with unmet physical activity need.
3. The association between higher fatigue and unmet physical activity appears to be reciprocal and to be explained by poorer health, poorer physical function, and or lower physical activity levels.
4. Lower levels of physical activity and reduced physical activity and neighborhood mobility predict the development of unmet physical activity need in old age.

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ORIGINAL PAPERS

I

COMMENT ON “FATIGABILITY: A PROGNOSTIC INDICATOR OF PHENOTYPIC AGING”

by

Palmberg, L., Portegijs, E., Karavirta, L., & Rantanen, T. 2021.

The Journals of Gerontology Series A: Biological Sciences and Medical Sciences 76 (8), e159-e160.

DOI: 10.1093/gerona/glab059

Journals of Gerontology: Medical Sciences
cite as: *J Gerontol A Biol Sci Med Sci*, 2021, Vol. XX, No. XX, 1–2
doi:10.1093/gerona/glab059
Advance Access publication February 27, 2021

Letter to the Editor

Comment on "Fatigability: A Prognostic Indicator of Phenotypic Aging"

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Increasing research interest in fatigability has resulted in increased efforts targeted toward its assessment. We have read with great interest the article by Schrack et al. (1). The authors have made a valuable contribution to advance fatigability research among older adults by reviewing existing literature and frequently used measures. Fatigability has been divided into 2 dimensions; perceived fatigability and performance fatigability. The latter is characterized by decline in performance during a standardized task (2). Thus, people with higher performance fatigability will exhibit greater decline during tasks standardized to a certain demand level (eg, walking speed) than people with lower performance fatigability.

When assessing performance fatigability, there are some instances where a self-paced walking test is preferred, as it may better reflect daily life situations (3), especially among older people. We wish to propose an alternative computation method of performance fatigability during a self-paced 6-minute walk test (6MWT) to those mentioned in the article. Our method also aims to overcome some concerns that we perceive related to 2 measures utilizing self-selected pace of walking (3,4).

To clarify the concern that we have over these measures, we used the equation by Murphy et al. (4) as an example. The equation for computing performance fatigability based on 6MWT was described as follows:

$$\text{Fatigability 1} = \frac{a}{b} * 1,000 = \frac{\left(\frac{\text{MWS over 6 minutes}}{\text{MWS over first 2 minutes}}\right)}{\text{Total distance walked}} * 1,000$$

First, *a*, the ratio of average walking speed (MWS, m/s) relative to the beginning, is calculated. Then, to account for task demand, *a* is divided by total distance (m) walked during the test (*b*), and, to obtain meaningful scores, multiplied by 1,000. Authors report that higher scores indicate higher performance fatigability.

However, in line with the definition of performance fatigability, those experiencing largest *decline* in walking speed and the lowest overall walking speed would be expected to get highest total scores. To our best understanding, the above-mentioned equation produces highest scores for those walking generally at a slower pace (low *b*) but who *increase* their walking speed toward the end (high *a*). A greater slowing during the test results in lower scores, as ratio *a* decreases ($a < 1.0$) compared to having stable ($a = 1.0$) or increasing walking speed ($a > 1.0$). Those with overall slower walking speed get higher scores than faster walkers, as *b* decreases. Therefore, the measure seems to identify those walking slowly rather than higher performance fatigability per se.

We propose a modified computation method to overcome the limitation described above, and conducted an initial validation for this new equation.

We computed performance fatigability scores based on data from a self-paced 6MWT and used the ratio of change in lap times (s) rather than in walking speed (m/s) in the equation. We used lap times of the second (beginning) and second-to-last lap (end), based on the approach by Simonsick et al. (5).

$$\text{Fatigability 2} = \frac{a}{b} * 1,000 = \frac{\left(\frac{\text{Lap time end}}{\text{Lap time beginning}}\right)}{\text{Total distance walked}} * 1,000$$

Highest scores are obtained by those slowing their walking during the test ($a > 1.0$) and having lower overall walking speed (low *b*). Thus, higher scores indicate higher performance fatigability in line with its definition.

We used data from a population-based sample of 778 Finnish community-dwelling 75-, 80- and 85-year-olds participating in AGNES study (6). For the 6MWT, participants walked 40-m laps at their usual pace in an indoor corridor. Study measures included health, function, and physical activity, and alternative measures of fatigability. Fatigability measures were a modified perceived exertion

Table 1. Spearman Correlations With Other Fatigability Measures, and Measures of Health, Function, and Physical Activity, *n* = 778

	PEF	SFS	PFS	WD 500 m	10-m Gait Speed	SPPB	YPAS	Age	Chronic Conditions
Performance fatigability	0.67	0.42	0.49	0.46	−0.79	−0.56	−0.41	0.31	0.30

Note: PEF = perceived exertion fatigability during the 6-min walk test; PFS = Physical Fatigue Subscale of the Situational Fatigue Scale; SFS = total score of the Situational Fatigue Scale; SPPB = Short Physical Performance Battery; WD = self-reported walking difficulty over 500 m; YPAS = Yale Physical Activity Survey. $p < .001$ for all.

fatigability (PEF) during the 6MWT (4), and self-reports of the Physical Fatigue Subscale (PFS) and total score of the Situational Fatigue Scale (SFS). Other measures were usual 10-m gait speed, Short Physical Performance Battery, self-reported walking difficulty over 500 m, Yale Physical Activity Survey, age, and chronic conditions.

Correlations were tested with Spearman's rho. Our performance fatigability score showed a relatively strong correlation with PEF (rho 0.67) and moderate correlations with SFS (0.42) and PFS (0.49; Table 1). Correlations with other measures were in expected directions, and particularly strong for 10-m gait speed (0.79).

Theoretically, *Fatigability 2* fits better with the definition of performance fatigability than the earlier computation methods. An additional advantage is that fewer conversion steps are needed for the equation (ie, lap times are not converted to walking speed, or averages calculated). The initial validation reported here is promising, but more research is warranted. For example, more information is needed for optimal use of task demand in standardizing performance fatigability score when using self-paced walking tests.

Funding

The research was funded by Academy of Finland (310526 to T.R.) and the European Research Council (693045 to T.R.).

Conflict of Interest

None declared.

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II

ACTIVITY FRAGMENTATION, PHYSICAL ACTIVITY AND PATTERNS OF NIGHTTIME REST AMONG COMMUNITY-DWELLING OLDER PEOPLE

by

Palmberg, L., Rantalainen, T., Rantakokko, M., Karavirta, L., Myllyntausta, S. Leppä, H., Portegijs, E. & Rantanen, T. 2021

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III

THE ASSOCIATIONS OF ACTIVITY FRAGMENTATION WITH PHYSICAL AND MENTAL FATIGABILITY AMONG COMMUNITY-DWELLING 75-, 80-, AND 85-YEAR-OLD PEOPLE

by

Palmberg, L., Rantalainen, T., Rantakokko, M., Karavirta, L., Siltanen, S., Skantz, H., Saajanaho, M., Portegijs, E. & Rantanen, T. 2020

The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 75 (9), e103-e110.

DOI: doi.org/10.1093/gerona/glaa166

Journals of Gerontology: Medical Sciences
cite as: *J Gerontol A Biol Sci Med Sci*, 2020, Vol. 75, No. 9, e103–e110
doi:10.1093/gerona/glaa166
Advance Access publication July 2, 2020

Research Article

The Associations of Activity Fragmentation With Physical and Mental Fatigability Among Community-Dwelling 75-, 80-, and 85-Year-Old People

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Received: December 20, 2019; Editorial Decision Date: June 15, 2020

Decision Editor: Anne B. Newman, MD, MPH

Abstract

Background: Fatigue related to task standardized by duration and intensity, termed fatigability, could manifest as shortening of activity bouts throughout the day causing daily activity to accumulate in a more fragmented pattern. Our purpose was to study the association of activity fragmentation with physical and mental dimensions of fatigability.
Methods: A cross-sectional study of 485 community-dwelling 75-, 80-, and 85-year-old people using a thigh-worn accelerometer for 3–7 days. Activity fragmentation was studied as Active-to-Sedentary Transition Probability for 2 operational definitions of physical activity: accelerations equivalent to at least light physical activity and for upright posture. Physical fatigability was assessed as perceived exertion fatigability, performance fatigability severity, and with the Physical Fatigue Subscale of the Situational Fatigue Scale. Mental fatigability was assessed with the Mental Fatigue Subscale of the Situational Fatigue Scale and as a decrease in perceived mental alertness after a 6-minute walk test.
Results: Higher activity fragmentation was associated with higher self-reported physical fatigability, perceived exertion fatigability, and performance fatigability severity, independent of total activity minutes (β = 0.13–0.33, p < .05 for all). Higher activity fragmentation was not associated with mental fatigability in the fully adjusted models. The associations with fatigability indices were similar for both activity fragmentation indicators. Associations of activity fragmentation and performance fatigability severity were similar also among those with the highest intensity-based physical activity volume.
Conclusions: The findings provide support that studying fragmented activity patterns can be useful in identifying those at risk for high fatigability, even among those with relatively high physical activity level.

Keywords: Activity patterns, Adaptive strategies, Fatigue, Physical activity

Fatigue is a common symptom among older people. It may be described as a subjective and unpleasant symptom that interferes with an individual's ability to function at their normal level and manifests as feelings ranging from tiredness to exhaustion (1). Fatigue is a commonly reported barrier to physical activity and a reason for restricted activity (2,3). With advancing age and a decline in health, different daily activities may become increasingly fatiguing (4,5). Fatigability refers to fatigue related to a specific task, which is standardized by duration and intensity (6). Assessments of fatigability can be divided into perceived fatigue and performance fatigability, the latter referring to the magnitude of decrease in task performance (7). These assessment methods can be applied to different domains of fatigability, including physical and mental fatigability (7). People with higher fatigability may start modifying their physical activity behavior by pacing, resting, conserving energy, and avoiding fatigue-inducing activities in an attempt to remain below their fatigue threshold (5,6,8) while continuing their participation in specific activities (9). Adaptive behaviors occurring in the early phase of fatigability could potentially manifest as shortening of activity bouts throughout the day (10).

In old age, when functional capacity declines, activity patterns often become more fragmented, as maintaining longer bouts of physically demanding activities gets progressively harder (10,11). More fragmented patterns of physical activity are associated with lower functional ability (10), higher mortality risk (12), and higher physical fatigability (10). People perceiving higher physical fatigability are less physically active (13) and at an increased risk of decline in physical function (14). However, studies on the associations of activity fragmentation with a more comprehensive range of fatigability measures, including performance fatigability severity, are lacking.

Fatigability has also mental and emotional dimensions (5). Perception of physical fatigue can be described as a perceived lack of physical energy, whereas mental fatigue can be characterized as perceptions of, that is, mental tiredness or lack of energy to think (5). However, previous studies among older people have thus far mainly focused on physical fatigability (10,13,14). Thus, less is known about the relationship between physical activity and mental fatigability. A recent concept analysis of fatigability suggested that the perception of fatigue is not domain-specific, that is, mental fatigue could also be induced by physical activity and vice versa (5). This concept is supported by an earlier finding showing that higher mental fatigability was associated with a steeper decline in physical function (15). Higher mental fatigue may also lead to increased perceived effort in performing physical activity (16) and may therefore concur with more fragmented patterns of physical activity.

Accelerometers are commonly used in measuring bouts of movement and nonmovement in free-living conditions. However, the usefulness of categorizing accelerometer data based on intensity levels among older people has been contested in recent years (17). While the absolute intensity of physical activity often declines with age, for those with reduced physical capacity the relative intensity (ie, effort with respect to capacity) of daily activities may become higher (18,19). Similarly, for those with slower walking speed, the energetic cost of walking is often higher (20) and therefore they may not be capable of performing activities classified as vigorous based on absolute intensity. Furthermore, accelerometers may be limited in their ability to detect light intensity activities (17,21). Possible solutions to these issues could be to study activity fragmentation based on the movement of at least low absolute intensity (10,22) or solely on posture estimation. Posture estimation can be useful in evaluating physical behavior among older adults and can be accurately measured even among frail older people (23). Sedentary behavior can be defined as activities that are ≤1.5 metabolic equivalents (MET) and performed in a sitting, reclining, or lying posture (24). On these premises, any activity performed in an upright posture, including standing, that has an energy consumption of more than 1.5 MET will be categorized as active behavior (24). Most standing activities have been shown to have an energy consumption of more than 1.5 MET (25), and therefore activity could be categorized into sedentary and nonsedentary based solely on posture. However, this has not been systematically studied in population-based samples of older people.

In the present study, we explored whether higher activity fragmentation is associated with physical and mental dimensions of fatigability among community-dwelling 75-, 80-, and 85-year-old people. We hypothesized that higher activity fragmentation is associated with more pronounced mental and physical fatigability. We measured activity fragmentation in 2 ways. First, it was assessed as Active-to-Sedentary Transition Probability (ASTP) based on acceleration bouts equivalent to at least light physical activity. Second, to introduce a possible alternative for intensity-based assessments, we assessed it based on ASTP based on upright posture.

Method

Study Design and Participants

The present study is a part of the "Active Aging—resilience and external support as modifiers of the disablement outcome" (AGNES) project. The study protocol has been reported in detail elsewhere (26). Briefly, participants were 75-, 80-, and 85-year-old people residing in the Jyväskylä area in Central Finland and were recruited from the Finnish Population Register Centre. A total of 1021 people took part, of whom 495 wore a triaxial accelerometer (range ±16 g, 13-bit analog-to-digital conversion, sampled at 100 Hz, UKK RM42; UKK Terveyspalvelut Oy, Tampere, Finland) for 7–10 consecutive days following a home interview (27). In addition, participants completed a postal questionnaire and participated in assessments at the research center. In the current analyses, we included participants with at least 3 days of valid accelerometer data (n = 485). The study protocol followed the principles of the Declaration of Helsinki. The AGNES study has been approved by the Ethical Committee of the Central Finland Health Care District. All participants signed written informed consent.

Self-Reported Physical and Mental Fatigability in Daily Life

We measured fatigability in daily life with a Finnish version of the Situational Fatigue Scale (SFS) (28) during a face-to-face interview. The scale was translated into Finnish and the translation was carefully evaluated by the research group. Participants were asked to report on a 6-point scale (0 = not fatigued at all, 5 = extremely fatigued) how fatigued they get after performing different activities (eg, taking a walk for 1 hour, jogging for 20 minutes, hosting a social event for 30 minutes, and watching TV for 2 hours). The physical activity items were used to form a Physical Fatigue Subscale (PFS, 4 items, range 0–20) and the mental activity items to form a Mental Fatigue Subscale (MFS, 9 items, range 0–45) (28).

Nondrivers were not asked the question about fatigability after driving for an hour (n = 128). Furthermore, 114 participants (23%) had at least one missing item on the PFS and 28 participants (6%) had at least one other missing item on the MFS. Items with the most missing data were self-reported fatigue after jogging for 20 minutes (n = 107) or playing a ball game for 30 minutes (n = 89). We imputed missing data with the multiple imputation (MI) procedure in SPSS. Imputation was done based on responses to other items on the SFS, self-reported walking ability and modifications in climbing a flight of stairs and walking distances of 2 km and 500 m, self-rated health, 3 instrumental activities of daily living functions, 3 items from the Center for Epidemiologic Studies-Depression (CES-D) scale, and perception of sufficient health to go out and about (Supplementary Table 1). Activity fragmentation was also added to the imputation model, as the inclusion of predictors in imputation models has been shown to lead to less biased estimates (29). We created 20 data sets of imputed values, and pooled results were reported for the corresponding analyses.

Perceived Exertion Fatigability and Mental Fatigability After a 6-Minute Walk Test

Participants completed a modified 6-minute walk test (6MWT) at the research center. They walked 40-m laps for 6 minutes in an indoor corridor at their usual walking pace. Participants were allowed to use a walking aid, if necessary. Perceived exertion fatigability was assessed using a modified version of a method validated by Murphy et al. (30). Perceived exertion was assessed using the Borg Rating of Perceived Exertion Scale (RPE, range 6–20, 6 = no exertion and 20 = completely exhausted) before and after completing the 6MWT (31). *Perceived exertion fatigability* was then calculated by dividing RPE at the end of the 6MWT by RPE at the beginning of the walk and further dividing the result by meters walked during the 6MWT. The result was then multiplied by 1000, for reporting purposes. *Perceived mental fatigability* was assessed as perceived mental alertness both prior to and after the 6MWT using a modified version of a 7-point Likert scale (1 = mentally exhausted and 7 = very alert and energetic) introduced by Schnelle et al. (32). Participants were dichotomized into those who felt mentally less alert after the 6MWT than before performing the test and those who felt more energetic or reported no change.

Performance Fatigability Severity

Performance fatigability severity was assessed during the 6MWT. We assessed the proportion of change in lap times between the second and the second-to-last 40-m lap, relative to walking speed during the entire 6MWT. This was done to account for potential faster-than-average starting during the first lap and anticipation of the finish during the last lap (33). Performance fatigability severity was then calculated by using a modified version of the method introduced by Schnelle et al. (32) and has been further validated for the 6MWT (30). We modified the method to better incorporate slowing down of performance into the formula. Our calculation was done by dividing the second-to-last lap time (s) by the second lap time (s). The result was further divided by the total distance walked (m) during the 6MWT to account for walking speed and multiplied by 1000 for reporting purposes. Higher performance fatigability severity scores indicate a more slowing down of performance relative to walking speed.

Activity Fragmentation

Activity fragmentation data were derived from the accelerometer recordings. Accelerometers were attached to the participants' dominant thigh with self-adhesive film. Although the film was waterproof, longer water-related activities such as swimming or taking a bath or sauna were not recommended while wearing the monitor. Participants completed an activity diary in which they reported any potential breaks in wearing the accelerometer and engaging in physical activities other than walking (26).

The method for physical activity quantification and posture estimation based on accelerometer recordings have been reported elsewhere (27). Briefly, the resultant accelerations were calculated for sampling instants and mean amplitude deviation (MAD) for nonoverlapping 5-second epochs. Mean daily minutes spent in at least light activity were based on a MAD value of at least 16.7 mg which has been shown to differentiate typical sedentary tasks from slow walking (34). Posture estimation was done following the approach by Vähä-Ypyä et al. (35). Postures were categorized into 2 categories: either sitting or lying down and upright. Posture categories for each 5-second epoch were then identified. The median posture category for each minute of recording was then used to calculate mean daily minutes spent in an upright posture (27). Accelerometer recordings were then used to determine active time based on intensity (at least light activity) and posture (standing still or moving in an upright posture). Based on the recordings, mean minutes of daily active time, mean number of active daily bouts, and mean bout duration in minutes based on both intensity (MAD-activity) and posture criteria (Posture-activity) were recorded.

Activity fragmentation was assessed as ASTP (10,22). Active-to-Sedentary Transition Probability was calculated separately for mean daily minutes based on MAD values classified as at least light activity (MAD-ASTP) and mean daily minutes spent in an upright posture (Posture-ASTP). This was done by dividing the mean active daily bouts by the mean sum of active daily minutes (22). Posture-ASTP and MAD-ASTP were categorized into tertiles for group comparisons. In all other analyses, MAD-ASTP and Posture-ASTP were used as continuous variables. Higher values in MAD-ASTP and Posture-ASTP indicate higher activity fragmentation. Results are reported per 0.1-point increase in the ASTP measures.

Covariates

Covariates were selected based on existing literature and their association with at least one of the predictors and the outcome variables. Age and sex were derived from the population register. Total years of full-time education were self-reported. Lower extremity function was measured with the Short Physical Performance Battery (range 0–12; higher scores indicate better lower extremity function). The test includes balance, walking speed, and chair stands (36). Global cognitive function was assessed with the Mini-Mental State Examination (range 0–30; higher scores indicate better cognitive function) (37). Depressive symptoms were measured with the CES-D scale (range 0–60; higher scores indicate more depressive symptoms) (38). Self-reported physician-diagnosed chronic conditions were ascertained with the help of a list of common chronic conditions. For each condition, participants were asked whether a physician has told them that they have that condition. Physician-diagnosed chronic conditions that were not included in the list were asked with additional open-ended questions (26). The number of chronic conditions was then calculated as the sum of individual chronic conditions. In addition, accelerometer-based mean Posture-activity and MAD-activity minutes were used as covariates.

Statistical Methods

Descriptive statistics by tertiles of ASTP included percentages for categorized variables and means with standard deviations for continuous variables. Group differences were analyzed with chi-square test for categorical variables, one-way analysis of variance for normally distributed continuous variables, and Kruskal–Wallis test for nonnormally distributed continuous variables. We used linear regression analysis to study associations of activity fragmentation and the continuous fatigability measures. Preliminary analyses suggested that the distribution of the MFS was skewed toward the lower end of scores and therefore we categorized the scale into quartiles of mental fatigability for further analyses. Ordinal regression analyses were performed to study the association of activity fragmentation with the quartiles of MFS. Binary logistic regression analyses were performed to study the association of activity fragmentation and perceived mental fatigability after the 6MWT. Models were first adjusted for age and sex and further for education, number of chronic conditions, lower extremity function, cognition, and depressive symptoms. Finally, to assess whether the amount of physical activity explained the association of activity fragmentation and fatigability, we added mean Posture-activity minutes into the models that included Posture-ASTP and mean MAD-activity minutes into the models that included MAD-ASTP.

Furthermore, we performed additional sensitivity analyses. First, we re-ran our analyses using the nonimputed data to see whether MI affected our findings. Second, we performed activity-stratified analyses on the association of activity fragmentation with mental and physical activity to see whether similar associations can be found among participants in all activity levels. Stratifying was performed according to tertiles of mean activity minutes (high activity, moderate activity, and low activity) separately for posture- and MAD-based activity.

IBM SPSS Statistics 24 for Windows was used for all analyses. Results were considered statistically significant when p value was less than .05 or when confidence intervals (CIs) for odds ratios (ORs) did not include one.

Results

Descriptive information on the participants is presented in Table 1, and fatigability and physical activity characteristics, according to the Posture-ASTP tertiles, in Table 2. These results largely resembled those found for the tertiles of MAD-ASTP, and hence, only group differences based on Posture-ASTP are reported. Those in the highest fragmentation tertile had higher self-reported physical fatigability scores ($p < .001$), perceived exertion fatigability ($p < .001$), and performance fatigability severity ($p < .001$) than those in the lowest fragmentation tertiles. In addition, they were more likely to experience higher perceived mental fatigability after the 6MWT ($p = .013$) but did not differ in self-reported mental fatigability ($p = .103$). Furthermore, those in the highest fragmentation tertile were more likely to be female ($p = .004$), have slightly lower physical function ($p = .032$), more chronic conditions ($p = .002$), fewer mean daily active minutes based on both MAD values and posture ($p < .001$), and more but shorter active bouts based on posture ($p < .001$ for both) and less and shorter active bouts based on MAD values ($p < .01$ for both). In addition, those in the highest fragmentation tertile had slightly lower cognitive function ($p = .020$). The groups did not differ in age, education, or depressive symptoms.

Posture-ASTP and MAD-ASTP correlated moderately with each other (Spearman's rho = .39, $p < .001$) and both were associated with higher performance fatigability severity (*Posture-ASTP*, $B = 0.44$, $SE = 0.05$; *MAD-ASTP*, $B = 0.35$, $SE = 0.04$; $p < .001$ for both; reported per 0.1 unit increase), higher perceived exertion fatigability after the 6MWT (*Posture-ASTP*, $B = 0.70$, $SE = 0.09$; *MAD-ASPP*, $B = 0.62$, $SE = 0.08$; $p < .001$ for both) and higher self-reported physical fatigability (PFS) in daily activities (*Posture-ASTP*, $B = 2.89$, $SE = 0.34$; *MAD-ASTP*, $B = 2.65$, $SE = 0.32$; $p < .001$ for both). The associations attenuated but remained statistically significant after controlling for covariates and after adding mean Posture- or MAD-activity minutes into the models (Table 3).

Among our study group, 33% perceived more mental fatigue after the 6MWT than before the test. Posture-ASTP, but not MAD-ASTP, was associated with higher perceived mental fatigability after the 6MWT (*Posture-ASTP*, OR 1.78, 95% CI 1.23–2.59) when adjusted only for age and sex. However, the association was attenuated and no longer statistically significant after adjusting for education, depressive symptoms, cognition, physical performance, and number of chronic conditions. Both Posture-ASTP and MAD-ASTP were associated with increased odds for higher self-reported mental fatigability (*Posture-ASTP*, OR 1.67, 95% CI 1.23–2.28; *MAD-ASTP*, OR 1.63, CI 1.24–2.15); however, the associations were attenuated after adjusting for education, depressive symptoms, cognition, physical performance, and number of chronic conditions (Table 4).

Sensitivity analyses showed that imputation did not materially affect our findings. In the activity-stratified analyses, the association of Posture-ASTP and MAD-ASTP with performance fatigability severity was similar even in the most active group according to MAD-activity. In addition, similar associations were found between Posture-ASTP and performance fatigability severity and self-reported physical fatigability in the highest Posture-activity group, although these associations did not reach statistical significance plausibly due to the small group size. The association of Posture-ASTP with mental fatigability was observed only in the lowest activity groups.

Discussion

In the present study, we found associations between more fragmented activity patterns and higher self-reported physical fatigability, perceived exertion fatigability, and performance fatigability severity, independent of total activity minutes. Furthermore, we found associations between more fragmented patterns of activity and higher mental fatigability, but these associations were attenuated in the fully adjusted models. Activity fragmentation among older people is a recent research interest, and, to the authors' best knowledge, only one previous study thus far has reported on the associations between activity fragmentation and perceived physical fatigability (10). This study expands previous findings by showing

Table 1. Descriptive Characteristics of Participants by Activity Fragmentation (ASTP) Tertiles Based on Posture

	Low Tertile (n = 163)	Middle Tertile (n = 161)	High Tertile (n = 161)	
	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	p Value
Age	78.3 (3.2)	78.4 (3.5)	78.3 (3.6)	.856*
Years of education	11.6 (4.2)	11.9 (4.2)	11.4 (4.4)	.303*
Lower extremity function	10.6 (1.8)	10.5 (1.6)	9.9 (2.2)	.032*
Cognitive function	27.8 (2.2)	27.4 (2.4)	27.0 (2.6)	.020*
Depressive symptoms	7.8 (6.6)	7.1 (6.5)	8.5 (6.7)	.079*
Number of chronic conditions	2.9 (1.9)	3.1 (2.1)	3.7 (2.0)	.002*
Female %	67.5	61.7	49.7	.004†

Note: ASTP = Active-to-Sedentary Transition Probability.
*Kruskal–Wallis test.
†Chi-square test.

Table 2. Physical Fatigability, Mental Fatigability, and Physical Activity Characteristics of Participants According to Activity Fragmentation (ASTP) Tertiles Based on Posture

	Low Tertile (n = 163)	Middle Tertile (n = 161)	High Tertile (n = 161)	
	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	*p* Value
Fatigability				
PFS subscale (range 0–20)	7.5 (4.5)	8.3 (4.2)	10.3 (5.0)	<.001*
Perceived exertion fatigability	2.8 (0.7)	3.1 (0.8)	3.5 (1.6)	<.001†
Performance fatigability severity	2.3 (0.4)	2.5 (0.6)	2.7 (0.7)	<.001†
Higher perceived mental fatigability after the 6MWT (%)	31.3	26.3	41.7	.013‡
Self-reported mental fatigability quartiles (%)	36	31	25	.103‡,§
Lowest	22	27	21	
Lower middle	26	27	29	
Higher middle	16	15	25	
Highest				
Physical activity				
Bouts per day				
Posture	36.2 (6.3)	41.1 (7.9)	44.2 (10.0)	<.001*
MAD	82.4 (15.5)	78.6 (14.0)	76.2 (16.3)	.001*
Active minutes per day				
Posture	424.5 (79.6)	327.3 (60.7)	238.3 (70.0)	<.001*
MAD	399.9 (87.7)	351.4 (76.8)	302.5 (88.0)	<.001*
Average bout length				
Posture	12.0 (2.7)	8.0 (0.7)	5.4 (1.1)	<.001*
MAD	5.0 (1.3)	4.5 (0.9)	4.0 (0.9)	<.001*
6MWT (m)	443.4 (68.6)	420.3 (72.1)	390.3 (92.6)	<.001*

Note: ASTP = Active-to-Sedentary Transition Probability; MAD = mean amplitude deviation; 6MWT = 6-minute walk test.
*One-way analysis of variance.
†Kruskal–Wallis test.
‡Chi-square test.
§The median of imputed *p* values reported.

Table 3. Associations of Activity Fragmentation (ASTP) Based on Posture and MAD Values With Physical Fatigability

	Model 1				Model 2				Model 3				
	B	*SE*	β	*p*	*B*	*SE*	β	*p*	*B*	*SE*	β	*p*	R^{2*}
Self-reported physical fatigability, range 0–20													
Posture-ASTP	2.89	0.34	0.36	<.001	2.02	0.33	0.25	<.001	1.53	0.52	0.19	.003	0.35
MAD-ASTP	2.65	0.32	0.36	<.001	1.57	0.33	0.21	<.001	0.92	0.46	0.13	.046	0.33
Perceived exertion fatigability													
Posture-ASTP	0.70	0.09	0.32	<.001	0.57	0.10	0.26	<.001	0.66	0.16	0.31	<.001	0.20
MAD-ASTP	0.62	0.08	0.33	<.001	0.49	0.09	0.26	<.001	0.43	0.13	0.23	.001	0.19
Performance fatigability severity													
Posture-ASTP	0.44	0.05	0.40	<.001	0.31	0.04	0.28	<.001	0.37	0.07	0.33	<.001	0.50
MAD-ASTP	0.35	0.04	0.36	<.001	0.21	0.04	0.21	<.001	0.16	0.06	0.17	.004	0.47

Notes: ASTP = Active-to-Sedentary Transition Probability; MAD = mean amplitude deviation; *B* = unstandardized regression coefficient; SE = standard error; β = standardized regression coefficient. Posture-ASTP and MAD-ASTP reported per 0.1 unit increase. Model 1 adjusted for age and sex; Model 2 adjusted for age, sex, education, physical performance, cognition, depressive symptoms, and number of chronic diseases; Model 3 total activity minutes added to the fully adjusted model.
*R^2 for fully adjusted model.

that, in addition to perceived exertion fatigability, more fragmented patterns of activity are associated with higher self-reported physical fatigability and higher performance fatigability severity.

Activities approaching the maximum energetic limit, irrespective of the maximum, will likely lead to fatigue. To avoid fatigue older people may modify their way of doing different tasks to conserve energy and reduce task demand (4–6,8). This may allow them to aggregate a relatively high volume of total physical activity in the course of the day by pacing the activities into shorter periods and avoiding longer bouts of continuous activity. The present findings are in line with earlier findings (10), suggesting that more fragmented physical activity patterns may be more important in identifying older individuals with increasing physical fatigability than total activity minutes. We found that among those with rather

Table 4. The Associations of Activity Fragmentation (ASTP) Based on Posture and MAD Values With Mental Fatigability

	Model 1	Model 2	Model 3
	OR (95% CI)	OR (95% CI)	OR (95% CI)
Higher perceived mental fatigability after 6MWT vs no change*			
ASTP (Posture)	1.78 (1.23–2.59)	1.47 (0.99–2.19)	1.79 (0.94–3.40)
ASTP (MAD)	1.20 (0.87–1.66)	0.91 (0.63–1.32)	0.88 (0.52–1.48)
Self-reported mental fatigability quartiles†			
ASTP (Posture)	1.67 (1.23–2.28)	1.19 (0.86–1.64)	1.12 (0.68–1.86)
ASTP (MAD)	1.63 (1.24–2.15)	1.09 (0.80–1.49)	0.92 (0.59–1.42)

Note: ASTP = Active-to-Sedentary Transition Probability; CI = confidence interval; MAD = mean amplitude deviation; OR = odds ratio; 6MWT = 6-minute walk test. Posture-ASTP and MAD-ASTP reported per 0.1 unit increase. Model 1 adjusted for age and sex; Model 2 adjusted for age, sex, education, physical performance, cognition, depressive symptoms, and number of chronic diseases; Model 3 total activity minutes added to the fully adjusted model.

*Data were analyzed with binary logistic regression analysis.

†Data were analyzed with ordinal logistic regression analysis.

high total physical activity, fragmented patterns of physical activity could be an early sign of increasing physical fatigability also and thus could have the potential to serve as a more sensitive indicator of impending high fatigability compared to total minutes spent in physical activity. With increasing fatigability, older people may reduce or avoid fatigue-inducing activities (5,6). Reducing physical activities, in turn, may lead to a reduced level of fitness, less energy available for physical activities, and consequently even higher fatigability related to specific physical activities (8). Identifying individuals at risk for high fatigability is thus important for preventing further increase in fatigability.

Our finding concerning mental fatigability can lay grounds for future studies on the topic, but need to be interpreted with some caution. The associations between activity fragmentation and mental fatigability were attenuated in our models after controlling for demographic and health factors as well as the activity levels of the participants. This suggests that poorer health and concurring low physical activity may underlie the association of activity fragmentation and mental fatigability, a potentially interesting future research topic. However, another interesting observation may stem from methodological challenges. Our participants aged 75, 80, or 85 years reported lower mental fatigability than the 18- to 60-year-old people participating in the SFS validation study (28). This was unexpected because one might expect that fatigability in the context of demanding mental and social activities will increase with age. It is possible that people of different ages evaluate their fatigue level in relation to some MFS subscale items based on different grounds. Some items may be more relevant for working-age people. However, it is also possible that with increasing age people gain experience, for example, about hosting social events which reduces accompanying mental fatigability. It has also been reported that after retirement there will be less of a burden of mental tasks than while in working life, leading to lower mental fatigue (5). In the future, it will be important to carefully evaluate and develop the assessment methods of mental fatigability in different contexts and age groups to gain knowledge of whether mental fatigability declines with increasing age or not. The Pittsburgh Fatigability Scale has been developed specifically for older adults and designed to overcome some of the pitfalls involved with the SFS, such as including items not normally performed by older people and failure to normalize activities to intensity levels (39). However, the mental subscale may not be able to capture fatigue related to mental work (40), further supporting the need for methodological development of self-reported mental fatigability tools among older people. Another interesting observation in the current study was that a third of the participants felt mentally more fatigued after performing a mainly physical task, the 6MWT, compared to before the task. This provides further evidence for an earlier suggestion that the perception of fatigability can cross over into different domains (5), that is, a physical task can lead also to mental fatigue and vice versa. However, the measure that was available for us to rate mental fatigability before and after the 6MWT has not been originally validated as a measure of mental fatigability, but is a measure of perceived change in tiredness related to a walk test, which we modified for the purpose of assessing changes in perceived mental alertness (32). Nevertheless, the current study supports methodological development for perceived mental fatigability assessment and further studies on mental fatigability with aging.

To the authors' best knowledge, this is the first study that has studied activity fragmentation based on posture estimation. A few previous studies have studied activity fragmentation based on accelerations representing at least light activity (10,22). In the present study, we evaluated activity fragmentation among older people by comparing both of these measures. The 2 ASTP measures showed only a moderate correlation with each other and would, therefore, seem to describe different aspects of physical activity patterns. However, we found similar associations between both ways of measuring activity fragmentation and fatigability, and thus ASTP based on posture also shows promise as a way of identifying older people at risk for high fatigability. Both measures were associated with lower overall activity minutes and shorter active bouts, which translate into more time spent in sedentary or stationary behaviors. However, some participants showed significant differences in their MAD- and posture-based total activity minutes (eg, 142.3 vs 556.0 minutes). Furthermore, while the highest MAD-ASTP tertile contained more women than men, women were more likely to be in the lowest tertile of Posture-ASTP. These differences may be explained by the lower physical capacity of women and/or by differences in the kinds of activities that men and women engage in. Women may be more involved in household chores than men, which may include more stopping while remaining in an upright posture.

The strengths of this study include a relatively large probability sample of community-dwelling participants. This will alleviate selection bias often evident in convenience samples. Participants wore an accelerometer continuously for 3–7 days, which provides an opportunity to control for day-to-day variation in physical activity volume and patterns. The possibility to assess physical activity objectively using both MAD and posture was a further strength, as it enabled us to compare these different activity fragmentation measures.

Furthermore, using several measures of fatigability strengthened our findings, and we were able to distinguish between self-reported physical fatigability, perceived exertion fatigability, performance fatigability severity, and self-reported and perceived mental fatigability and their associations with activity fragmentation. In addition, we used a modified version of the performance fatigability scale, which was able to better incorporate performance deterioration measured as slowing down during the 6MWT.

The study also has limitations. First, the data were cross-sectional and thus do not permit conclusions on the temporal associations between activity fragmentation and fatigability. Therefore, future longitudinal studies are called for. Second, the fatigability measures that we used involve some limitations. The SFS has been validated among 18- to 60-year-old people and thus may not be ideal for assessing fatigability among older adults. The PFS includes activities that may not be typically performed by older people, such as jogging and playing ball games, and the distribution of the MFS suggests that the subscale may not be the ideal instrument for evaluating mental fatigability among older people. Nevertheless, these results were in line with our other results and thus strengthen our findings. Furthermore, we used modified versions of the originally validated measures for perceived exertion fatigability and mental fatigability during the 6MWT which may affect our findings. However, the original validated calculation method for perceived exertion fatigability was problematic in our study, as all participants with no change in perceived exertion regardless of walking speed and initial RPE rating, would get a score of zero. Using the slightly modified version of the method partly solved this issue and showed moderate to high correlations with the PFS subscale and performance fatigability severity scores (r = 0.42 and 0.72, respectively). Third, we used an acceleration cut point that has been originally developed for a waist-mounted device (34). As the accelerations on the thigh are generally higher than on the waist (41), using this cut point may overestimate the amount of at least light physical activity. However, because using intensity-based cut points for older people with decreasing physical function poses challenges (17–19), and similar intensity in different physical activities produces different accelerometer readings, we wanted to use a cut point low enough to capture all slow movement. The average active minutes using the MAD-based cut point of 16.7 mg was fairly comparable to those determined by posture estimation (350 vs 329 minutes), and thus, large overestimations of active minutes seem unlikely. Future studies targeting the differences between posture- and cut point-based measures of physical activity patterns are warranted. Finally, the older adults who participated in our study had generally better health than those not willing to participate (27), and thus, our findings may underestimate fatigability among the community-dwelling older population.

Conclusions

More fragmented patterns of activity are associated with higher self-reported physical fatigability, perceived exertion fatigability, and performance fatigability severity among community-dwelling older persons. The findings on activity fragmentation and performance fatigability severity were similar even among those who accrued relatively high mean levels of physical activity. Thus, activity fragmentation can be a sign of impending fatigability even though activity levels continue to remain high. The findings of this study are in line with earlier discoveries that studying fragmented activity patterns can be useful in identifying those at higher risk for high fatigability, although future longitudinal studies are needed to study the temporal associations between activity fragmentation and fatigability. Although we did not find associations between activity fragmentation and mental fatigability in the fully adjusted models, the findings also suggest that physical activities can be experienced as mentally fatiguing and vice versa. This suggests that it may be beneficial to pay more attention to mental fatigue in the physical activity context, but may also require further development of methods of studying perceived mental fatigability among the older population. In addition, studying activity fragmentation based on both acceleration and body posture may be fruitful in future research, because these methods seem to describe somewhat different aspects of physical activity patterns.

Supplementary Material

Supplementary data are available at *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences* online.

Funding

This work was supported by the European Research Council (693045 to Ta.R.); the Academy of Finland (321336 and 328818 to Ti.R. and 310526 to Ta.R.); the Finnish Ministry of Education and Culture (to M.R. and E.P.) and the University of Jyvaskyla. The content of this manuscript does not reflect the official opinion of the European Union. Responsibility for the information and views expressed in the manuscript lies entirely with the authors.

Acknowledgments

The Gerontology Research Center is a joint effort between the University of Jyvaskyla and the University of Tampere. The authors wish to acknowledge the CSC—IT Center for Science, Finland, for computational resources.

Author Contributions

Concept and design (L.P., Ti.R., M.R., L.K., S.S., H.S., M.S., E.R., and Ta.R.), acquisition of data (L.P., Ti.R., M.R., L.K., S.S., H.S., M.S., E.R., and Ta.R.), analysis and/or interpretation of data (L.P., Ti.R., M.R., L.K., S.S., H.S., M.S., E.R., and Ta.R.), drafting the article (L.P.), critical revision of the article (Ti.R., M.R., L.K., S.S., H.S., M.S., E.R., and Ta.R.). All authors approved the article.

Conflict of Interest

None declared.

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IV

THE RELATIONSHIP BETWEEN SLEEP CHARACTERISTICS AND UNMET PHYSICAL ACTIVITY NEED IN OLDER WOMEN

by

Palmberg, L., Viljanen, A., Rantanen, T., Kaprio, J. & Rantakokko, M. 2020

Journal of Aging and Health, 32 (3-4), 199-207.

DOI: doi.org/10.1177/0898264318814021

Article

Journal of Aging and Health
2020, Vol. 32(3-4) 199–207

DOI: 10.1177/0898264318814021
journals.sagepub.com/home/jah
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The Relationship Between Sleep Characteristics and Unmet Physical Activity Need in Older Women

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Abstract

Objective: We examined among older women the association of sleep quality, daytime tiredness, and sleep duration with unmet physical activity need, that is, wishing to be more physically active but perceiving no opportunity for it. **Method:** Cross-sectional logistic regression analyses among women aged 74 to 86 years (Finnish Twin Study on Aging, third wave, n = 302). **Results:** Thirty-one participants reported unmet physical activity need. Short sleepers had fivefold and long sleepers threefold odds for unmet physical activity need compared with normative sleepers, while for daytime tiredness the odds were double. Presence of daytime tiredness and unmet physical activity coincided with higher prevalence of chronic diseases, depressive symptoms and walking difficulties, which partly explains the observed associations. Poor sleep quality was not associated with unmet physical activity need. **Discussion:** Older women with nonoptimal sleep characteristics who perceive unmet physical activity need may benefit from solutions that improve their perceived opportunities for physical activity.

Keywords

unmet physical activity need, sleep duration, sleep quality, daytime tiredness, aging

Physical activity has been defined as "any bodily movement produced by skeletal muscles that results in energy expenditure" (Caspersen, Powell, & Christenson, 1985, p. 126) and can be considered as a basic human need. Both physiological and psychological basic needs can be defined as "energizing states that, if satisfied, conduce toward health and wellbeing but, if not satisfied, contribute to pathology and ill-being" (Ryan & Deci, 2000, p. 74). Remaining physically active and having the opportunity to participate in physical activities in old age is important, due to its positive effects on physical and psychological health (Penedo & Dahn, 2005; Warburton, Nicol, & Bredin, 2006). However, many older adults perceive that they do not have the opportunity to be more physically active even though they would want to do so and thus experience unmet need for physical activity (Rantakokko et al., 2010). Unmet physical activity need refers to a person's own experience of inadequate physical activity (Rantakokko et al., 2010) and is therefore distinct from fulfilling the level of physical activity that is recommended in the physical activity guidelines for older adults (Nelson et al., 2007). Prior research on unmet needs has mainly focused on issues such as safety, financial resources, and assistance in self-care and mobility-related tasks. Unmet basic needs have been associated with several adverse consequences among older people. Unmet need of assistance in mobility-related activities can lead to inability to leave one's home or even bed (Allen, Piette, & Mor, 2014). Furthermore, unmet basic needs have been found to predict depressive symptoms (Blazer, Sachs-Ericsson, & Hybels, 2007), functional decline (Sachs-Ericsson, Schatschneider, & Blazer, 2006), and mortality (Blazer, Sachs-Ericsson, & Hybels, 2005) and thus, unmet physical activity need may potentially have very harmful consequences in the lives of older people.

In earlier population-based studies in Finland, 14% of respondents experienced unmet physical activity need making it a relatively common phenomenon (Eronen et al., 2014; Rantakokko et al., 2010). The few studies among older adults have shown that unmet physical activity need is more common among older adults with mobility limitations, depressive symptoms, and musculoskeletal diseases (Rantakokko et al., 2010) and that persons with severe mobility limitations

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are at an increased risk for unmet need for physical activity (Eronen et al., 2014). Studies on the associations of sleep and daytime tiredness with unmet physical activity need are, however, lacking.

As people age, their sleep goes through several changes and the prevalence of sleep disturbances increases (Ohayon, Carskadon, Guilleminault, & Vitiello, 2004); this is often related to physical and mental disorders and diseases (Vitiello, Moe, & Prinz, 2002). Poor sleep is associated with lower physical activity levels (Li et al., 2018), decreased health-related quality of life (Reid et al., 2006), various adverse health outcomes and diseases (Ancoli-Israel, 2009), less healthy and disease-free life years (Stenholm et al., 2018) and mortality (Hublin, Partinen, Koskenvuo, & Kaprio, 2011). Many studies have found a U-shaped relationship between sleep duration and different adverse health outcomes, showing that both short (≤5-6 hr) and long (>8-9 hr) sleep duration are associated with adverse health outcomes, less disease-free and healthy life years, and mortality (Cappuccio, Cooper, D'Elia, Strazzullo, & Miller, 2011; Cappuccio, D'Elia, Strazzullo, & Miller, 2010a, 2010b; Hublin, Partinen, Koskenvuo, & Kaprio, 2007; Stenholm et al., 2018). In addition, short sleep duration has been found to be associated with mobility limitations (Lorenz, Budhathoki, Kalra, & Richards, 2014; Stenholm et al., 2010) and both long sleep duration and short subjective sleep duration have been found to predict functional decline (Stenholm, Kronholm, Bandinelli, Guralnik, & Ferrucci, 2011). Although tiredness is commonly known as one of the symptoms of sleep disorders or a symptom of other physiological and psychological diseases, many older adults experience tiredness with no clear cause (Avlund, 2010). Previous studies have shown that mobility-related and general tiredness is associated with lower physical activity levels (Egerton, Chastin, Stensvold, & Helbostad, 2016) and can predict the onset of adverse health outcomes, such as walking limitations (Avlund et al., 2004), poorer physical functioning and disability (Avlund, Damsgaard, Sakari-Rantala, Laukkanen, & Schroll, 2002; Manty, Kuh, & Cooper, 2015; Schultz-Larsen & Avlund, 2007), and mortality (Hardy & Studenski, 2008; Moreh, Jacobs, & Stessman, 2010).

Because people who sleep poorly or experience daytime tiredness are more likely to have activity limitations, it is plausible that they also perceive reduced possibilities for physical activity. However, information on the relationship between sleep, tiredness, and unmet physical activity need is lacking. The aim of this study was to examine whether poor perceived sleep, daytime tiredness, and sleep duration are associated with unmet physical activity need among older women. We hypothesized that older women with poor perceived sleep quality, daytime tiredness, and short or long sleep duration are more likely to report unmet physical activity need.

Method

Study Design and Participants

Participants were 344 women, aged 74 to 86, who took part in the third wave of Finnish Twin Study on Aging (FITSA) in 2011-2012 when the assessment of unmet physical activity need was added to the study protocol. The FITSA sample ($N = 434$) was drawn in 2000-2001 based on age, female sex, zygosity, and willingness to participate in the study from the Finnish Twin Cohort Study, a population-based sample of twins initially recruited from a population register. Compared with the 90 drop outs, the 344 people who took part also in the third wave were younger, had better financial situation, and experienced less walking difficulties and daytime tiredness, but were similar in terms of depressive symptoms, sleep quality, and sleep duration.

The third data collection wave was conducted as a postal questionnaire (Viljanen et al., 2013). Questionnaires were supplemented with telephone interviews in cases where participants had difficulties in answering the postal questionnaire. The concept of unmet physical activity need was launched in 2010 (Rantakokko et al., 2010) and consequently data on it are only available in this third data collection wave of FITSA. Data on unmet physical activity need were missing for 42 participants, and thus 302 women were included in the present analyses.

Unmet Physical Activity Need

Unmet physical activity need was measured with two questions. These were, "Do you feel that you would have the opportunity to increase your level of physical activity if someone recommended you do so?" and "Would you like to increase your level of physical activity?" For both questions, the response options were "yes" and "no." Persons, who wanted to increase their level of physical activity but felt they did not have the opportunity to do so, were defined as having unmet physical activity need (Rantakokko et al., 2010).

Sleep Duration, Perceived Sleep Quality, Napping, and Daytime Tiredness

Sleep characteristics were assessed with questions that measured perceived overall sleep quality, napping, and sleep duration. Sleep duration was measured with the question "How many hours on average do you habitually sleep per night?" For the analyses of this study, the response options were recoded into short (<6 hr), normative (6-8 hr), and long (>8 hr) sleep duration. A similar classification for short and long sleep duration has been used previously (Chien, Wang, & Chen, 2015). Self-reported sleep quality was measured with the question "How well do you usually sleep?" and for the analyses the answers were dichotomized as "well" (quite well and well) and "poor" (quite poorly or poorly). Participants who answered

"I am not sure" ($n = 7$) were excluded from the corresponding analyses. Napping was measured with the question "Do you usually sleep in the daytime?" and perceived daytime tiredness was measured with the question "Do you feel tired in the daytime daily or nearly daily?" The response options for these two questions were "yes" and "no."

Covariates

Age and financial situation of the participants were regarded as potential confounding factors. Other covariates were included in the models based on their theoretical and statistically significant association with unmet physical activity need and at least one of the sleep characteristics.

Perceived financial situation. Perceived financial situation was self-reported and dichotomized as "very good or good" and "moderate, poor, or very poor."

Walking difficulties. Mobility limitations can increase the risk for unmet physical activity need (Eronen et al., 2014) and daytime tiredness and sleep duration are associated with mobility limitations (Avlund et al., 2004; Stenholm et al., 2010). Participants' mobility limitations were assessed as walking difficulties, which were measured by asking whether the participant perceived difficulty walking 2 kilometers without stopping to rest. For the analyses, the response alternatives were dichotomized as "no difficulties" (able to manage without difficulty) and "difficulties" (minor difficulties, major difficulties, I need help or I am not able to).

Number of chronic diseases. Although in an earlier study unmet physical activity need has been found to be more common among older people with musculoskeletal diseases (Rantakokko et al., 2010), in this study we decided to adjust for number of chronic diseases because of its relevance also for sleep (Vitiello et al., 2002) and daytime tiredness (Avlund, 2010). Number of chronic diseases was self-reported and measured with a list of 22 common chronic diseases, and participants were asked to state for each condition whether they had been diagnosed with that condition by a physician or not. Participants were also asked to report any other physician-diagnosed chronic diseases.

Depressive symptoms. Depressive symptoms often coincide with unmet physical activity need (Rantakokko et al., 2010) and have also been associated with poor sleep and daytime tiredness (Maglione et al., 2012). Depressive symptoms were measured with the Center for Epidemiologic Studies Depression Scale (CES-D, range = 0-60, higher scores indicate more depressive symptoms) (Radloff, 1977).

Physical activity. Unmet physical activity need has been found to be more common among inactive older people (Eronen, von Bonsdorff, Rantakokko, & Rantanen, 2012), and daytime tiredness and poor sleep have been associated with lower activity levels (Egerton et al., 2016; Lambiase, Gabriel, Kuller, & Matthews, 2013). Physical activity was self-reported (Grimby, 1986) and categorized into sedentary (no more than light activity two or fewer times per week), moderate activity (light activity at least three times per week), and high activity (moderate or vigorous activity three or more times per week).

Sleep medication. Use of sleep medication was measured with a yes/no question.

Statistical Analyses

Participant characteristics were analyzed using means and standard deviations for continuous variables and percentages and frequencies for categorical variables according to unmet physical activity need. Comparisons of demographic characteristics, health, and walking limitations between the groups were made using Wald tests adjusted for the interdependency within twin pairs. The associations of daytime tiredness, perceived sleep quality, and sleep duration with unmet physical activity need were analyzed using logistic regression models. First model was age-adjusted; second model was adjusted for age, number of chronic diseases, and depressive symptoms; third model for age and walking difficulties; fourth model for age and physical activity; and the final model for age, chronic diseases, depressive symptoms, walking difficulties and physical activity. The dependency within twin pairs was controlled for in all the analyses. Missing observations in the explanatory variables (perceived sleep quality [$n = 4$], daytime tiredness [$n = 6$], and sleep duration [$n = 3$]) were imputed based on data from the previous data collection wave. Sensitivity analyses showed imputation strengthened the associations slightly but did not materially change the results.

Statistical analyses were conducted using Stata Statistical software Version 14 and IBM SPSS Statistics Version 24. The results were considered statistically significant when p value was $<.05$ or when 95% confidence intervals did not contain 1.

Results

The mean age of the participants ($n = 302$) was 79.0 years, and 10 % ($n = 31$) of them reported unmet physical activity need. The participant characteristics are shown in Table 1 according to whether they experienced unmet physical activity need or not. The largest proportion of participants in both groups reported habitual sleep duration of 6 to 8 hr, although this was more common in the group of participants without unmet physical activity need. Participants with unmet physical activity need were more likely to report very short and long habitual sleep duration ($p = .020$) and daytime tiredness ($p = .043$) than participants not experiencing unmet

Table 1. Demographic Characteristics of the Participants: Means, Standard Deviations, Percentages, Frequencies Are Shown (n = 302).

	Unmet physical activity need		
	Yes (n = 31)	No (n = 271)	
	M (*SD*)	*M* (*SD*)	p^a
Age	79.0 (3.4)	79.0 (3.3)	.986
Number of chronic diseases	5.1 (2.2)	3.9 (2.3)	.009
Depressive symptoms	19.7 (10.3)	13.6 (7.3)	.004
	% (*n*)	% (*n*)	
Sleep duration			.020
Less than 6 hr	32 (10)	11 (29)	
6-8 hr	55 (17)	82 (224)	
More than 8 hr	13 (4)	7 (18)	
Sleep quality			.150
Good	68 (21)	80 (212)	
Poor	32 (10)	20 (52)	
Daytime tiredness	61 (19)	41 (112)	.043
Taking naps	45 (13)	48 (129)	.846
Sleep medication use	40 (12)	22 (60)	.090
Walking difficulties	90 (27)	55 (145)	<.001
Physical activity			.001
Sedentary	71 (22)	39 (102)	
Moderate activity	26 (8)	43 (113)	
High activity	3 (1)	18 (47)	
Financial situation			.171
Good	20 (6)	31 (81)	
Moderate or poor	80 (24)	69 (184)	

Note. n = number of participants.
aWald test adjusted for interdependency within twin pairs.

physical activity need. The proportion of the participants using sleep medication was larger in the group reporting unmet physical activity need than in the group not experiencing unmet physical activity need; however, the difference was not statistically significant (p = .090). Participants with unmet physical activity need were more likely to have walking difficulties ($p < .001$), more chronic diseases (p = .009), more depressive symptoms (p = .004), and to be sedentary (p = .001) than the participants who did not experience unmet physical activity need. The groups were similar in mean age, financial situation, perceived sleep quality, and taking naps (Table 1). Of the covariates associated with unmet physical activity need, depressive symptoms, chronic diseases, walking difficulties, and physical activity were also associated with at least one sleep characteristic and were thus included in the multivariate models.

The results of the logistic regression analyses are presented in Table 2. For participants with short habitual sleep duration (<6 hr), the age-adjusted odds for unmet physical activity need were nearly fivefold compared with participants with normative sleep duration (odds ratio [OR] = 4.62, 95% confidence interval [CI] = [1.95, 10.98]). Adjusting for number of chronic diseases and depressive symptoms attenuated the association, but it remained statistically significant (OR = 3.23, 95% CI = 1.21, 8.65). While for participants with long habitual sleep duration the age-adjusted odds for unmet physical activity need were threefold, the association did not reach statistical significance (OR = 2.96, 95% CI = [0.88, 9.90]). Adjusting for walking difficulties slightly increased the odds for unmet physical activity need among short and long sleepers.

For participants who experienced daytime tiredness, the odds for unmet physical activity need were twofold when adjusted for age only (OR = 2.25, 95% CI = [1.04, 4.85]), but after adjusting for the other covariates the association was attenuated (OR = 0.87, 95% CI = [0.38, 2.01]) (Table 2). Higher prevalence of chronic diseases, depressive symptoms, physical activity, and walking difficulties attenuated the association between daytime tiredness and unmet physical activity need. For participants perceiving poor sleep quality, the odds for unmet physical activity need were twofold, but the association did not reach statistical significance (OR = 1.95, 95% CI = [0.88, 4.32]). We conducted additional analyses and adjusted the models separately for sleep medication use but observed no material effect on the association between sleep duration and unmet physical activity need.

Discussion

To the best of our knowledge, the present study is the first to examine the relationship of sleep- and rest-related factors with unmet physical activity need, that is, the will to be more physically active while perceiving poor opportunities to do so. Studies focusing on physical activity and sleep among older people have mainly targeted the positive effects of physical activity on sleep (Yang, Ho, Chen, & Chien, 2012) and fewer on the bidirectional association of physical activity and sleep (Holfeld & Ruthig, 2014; Lambiase et al., 2013). The present study adds to the current knowledge about the relationship between sleep and physical activity by showing that although insufficient sleep and daytime tiredness may coexist with perceiving decreased opportunities for physical activity, the wish to be physically more active remains. This finding will lay grounds for future studies on physical activity promotion among older people with sleeping problems.

There may be several explanations for the association between short sleep duration and unmet physical activity need. People who sleep insufficiently more often report lack of energy for performing daytime activities (Groeger, Zijlstra, & Dijk, 2004). Getting tired performing specific standard activities has been termed fatigability (Eldadah, 2010). Unfortunately, we did not have data on fatigability, but speculate that it may underlie the association between short sleep

Table 2. Associations of Sleep Characteristics With Unmet Physical Activity Need Among Older Women.

	Model 1[a] OR (95% CI)	Model 2[b] OR (95% CI)	Model 3[c] OR (95% CI)	Model 4[d] OR (95% CI)	Model 5[e] OR (95% CI)
Sleep duration					
<6 hr vs. 6-8 hr	4.62 [1.95, 10.98]	3.03 [1.14, 8.02]	4.71 [1.88, 11.84]	4.48 [1.84, 10.95]	3.23 [1.21, 8.65]
>8 hr vs. 6-8 hr	2.96 [0.88, 9.90]	2.04 [0.55, 7.55]	3.74 [1.08, 12.86]	2.74 [0.83, 9.03]	2.70 [0.74, 9.81]
Daytime tiredness	2.25 [1.04, 4.85]	1.15 [0.48, 2.78]	1.42 [0.67, 3.03]	1.70 [0.77, 3.74]	0.87 [0.38, 2.01]
Poor sleep quality	1.95 [0.88, 4.32]	1.35 [0.52, 3.57]	1.87 [0.83, 4.24]	1.93 [0.84, 4.36]	1.44 [0.55, 3.77]

Note. OR = odds ratio; CI = confidence interval.
[a]Model 1 adjusted for age.
[b]Model 2 adjusted for age, depressive symptoms, and number of chronic diseases.
[c]Model 3 adjusted for age and walking difficulties.
[d]Model 4 adjusted for age and physical activity.
[e]Model 5 adjusted for age, depressive symptoms, number of chronic diseases, walking difficulties, and physical activity. All models were adjusted for interdependency between twin pairs.

duration and unmet physical activity need. A recent study suggests an association between sleep duration and fatigability (Aldughmi, Huisinga, Lynch, & Siengsukon, 2016), while others report that fatigability reduces physical activity and increases the risk of functional decline (Simonsick et al., 2016; Wanigatunga et al., 2017). Older adults who get fatigued while participating in physical activities may start feeling that physical activity is not possible for them, a situation which may lead to unmet physical activity need.

While perceived fatigability is related to specific tasks (Eldadah, 2010), tiredness refers to a general subjective lack of energy and need for recovery (Ream & Richardson, 1996; Söderberg, Lundman, & Norberg, 2002). Perceived tiredness is a barrier to physical activity for many older people (Wilcox et al., 2006) and is associated with reduced levels of physical activity (Egerton et al., 2016). In the present age-adjusted models, daytime tiredness was associated with unmet physical activity need, but adjustment for the presence of walking limitations, depressive symptoms, and comorbidity attenuated the association. Tiredness predicts poorer physical functioning and disability (Avlund et al., 2002; Manty et al., 2015; Schultz-Larsen & Avlund, 2007) and can therefore affect older people's ability to walk. Because walking is a popular form of physical activity among older people (Lim & Taylor, 2005) and participation in other forms of physical activity may also require ability to walk (Rantakokko et al., 2010), difficulties in walking may substantially hinder a person's possibilities to be physically active and so lead to unmet physical activity need. Furthermore, because tiredness is associated with a variety of physiological and psychological conditions (Avlund, 2010), the medical conditions underlying tiredness may also cause physical limitations and hinder possibilities to engage in physical activity, which, again, may lead to unmet need for physical activity. Poor health has previously been found to be a risk factor for unmet physical activity need (Eronen et al., 2014), and depressive symptoms have been found to coincide with unmet physical activity need (Rantakokko et al., 2010).

Poorer general health and physical limitations caused by diseases may also limit older people's perceived opportunities for physical activity (Franco et al., 2015). Several studies have reported previously that sleep disturbances in late life often coincide with comorbidities (Ancoli-Israel, 2009; Vitiello et al., 2002), while short sleep may also indicate a tendency to have unhealthier habits (Stranges et al., 2008).

It is also possible that unmet physical activity need precedes a reduction in habitual sleep duration through reduced level of physical activity. Previous studies have shown that physical activity has beneficial effects on sleep (Yang et al., 2012), and consequently a reduction in physical activity, a known risk factor of unmet physical activity need (Rantakokko et al., 2010), may disturb sleep. In the current study, the association between short sleep duration and unmet physical activity need remained strong also after adjusting for self-reported physical activity; however, the question was rather crude and may not have captured all the variation in physical activity among the participants.

In the current study, long sleep duration showed threefold odds for unmet physical activity compared with those sleeping 6 to 8 hr. The association did not quite reach statistical significance due to small number of long sleepers in our sample (n = 22). Because long sleep duration has previously been associated with poor health and functioning (Cappuccio et al., 2011; Cappuccio et al., 2010a, 2010b; Stenholm et al., 2011), we speculate that it may also be associated with unmet physical activity need. This preliminary observation warrants more research in larger samples.

Sleep quality was not associated with unmet physical activity need in the present study. This may, however, be partly explained by the measure used to assess sleep quality, which was a single question designed to elicit participants' general perception of their overall sleep quality. Buysse, Reynolds, Monk, Berman, and Kupfer (1989) have described sleep quality as "a complex phenomenon that is difficult to define and measure objectively." Thus, while subjective perception of sleep quality is important, the fact that sleep quality comprises several objective and subjective dimensions (Buysse et al., 1989) means that these were not likely captured with a single question.

The main strength of this study is that it is based on population-based sample of older twin women. A further strength is that it yielded novel findings on the associations of sleep characteristics with unmet physical activity need, along with more information on the phenomenon of unmet physical activity need in the lives of older people. Furthermore, the study generated new hypotheses to be tested in future studies and the findings lay grounds for research on solutions for improving older people's opportunities for physical activity participation.

The study also has its limitations. First, the cross-sectional study setting does not allow conclusions to be drawn about the direction of the association between sleep duration and unmet physical activity need, leaving this topic for further study. Second, the relatively low prevalence of unmet physical activity need, although in line with previous findings (Eronen et al., 2014; Rantakokko et al., 2010), resulted in lack of statistical power in the analyses. This is likely due to the relatively good health and functional ability of the participants due to the study protocol of FITSA, which required the participants to be able to travel to the research laboratory from their town of residence at baseline (Viljanen et al., 2009). The findings are, therefore, limited to relatively high-functioning individuals and it is possible, therefore, that the results of this study underestimate the prevalence of unmet physical activity need among Finnish older women. Twin individuals are largely similar compared with singletons in terms of their health status (Andrew et al., 2001; Simmons et al., 1997) and do not differ in mortality (Kaprio, 2013), and therefore it is not likely that this affects the findings of this study. Third, this study was based on secondary analyses of the FITSA study, which was not specifically designed to study unmet physical activity need and sleep. Thus, sleep quality and sleep duration were assessed solely with single self-reports. Self-reported measures of sleep are commonly used in research but they may lead to over- or underestimations of sleep duration or sleep disturbances. People appear to overestimate their sleep duration in comparison to objectively measured sleep (Matthews et al., 2018), except for those reporting poor sleep quality who are more likely to underestimate their sleep duration (Vallières & Morin, 2003; Van Den Berg et al., 2008). In addition, self-reports of sleep duration often do not distinguish time spent sleeping from time spent in bed (Cappuccio et al., 2011; Stenholm et al., 2011). The correspondence between subjective and objective measures of sleep seems to change with advancing age and older people who sleep poorly objectively may perceive their sleep quality as good (Åkerstedt, Schwarz, Gruber, Lindberg, & Theorell-Haglöw, 2016; Vitiello, Larsen, & Moe, 2004). It is therefore likely that with increasing age the present participants had already modified their criteria of what constitutes good sleep quality, which may affect the results. Fourth, we cannot rule out the possibility that some other factor that we did not adjust for confounds the association between sleep and unmet physical activity need. Finally, the measure of unmet physical activity need was dichotomous and thus, the group of participants not experiencing unmet physical activity need is relatively heterogeneous.

Conclusion

The findings show that older women who sleep less than 6 hr per night may be more likely to experience unmet physical activity need. This study suggests that older women with other than normative sleep duration or daytime tiredness, who also experience unmet physical activity need, may benefit from solutions that promote their perceived opportunities for physical activity participation. In the future, larger studies including men and women and objective and subjective measures of sleep are needed to confirm the temporal order of events and eventually to lay grounds for potential interventions.

Acknowledgment

The Gerontology Research Center (GEREC) is a joint effort between the University of Jyväskylä and University of Tampere, Finland.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Finnish Ministry of Education and Culture; and Academy of Finland (grant 285747 to M.R., 251723 to A.V., 265240 & 263278 to J.K., and 69818 to T.R.). The financial sponsors played no role in the design, execution, analysis or interpretation of data, or writing of the study.

Research Ethics

The FITSA study was approved by the Ethics Committee of the Central Finland Health Care District. The study protocol has followed the good scientific and clinical practices laid out by the 1964 Declaration of Helsinki.

Consent to Participate

Written informed consent was obtained from all individual participants included in the study.

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NEIGHBORHOOD MOBILITY AND UNMET PHYSICAL ACTIVITY NEED IN OLD AGE: A 2-YEAR FOLLOW-UP

by

Palmberg, L., Portegijs, E., Rantanen, T., Aartolahti, E., Viljanen, A., Hirvensalo, M. & Rantakokko, M. 2019

Journal of Aging and Physical Activity, 28 (3), 442-447.

DOI: doi.org/10.1123/japa.2019-0047

Neighborhood Mobility and Unmet Physical Activity Need in Old Age: a Two-Year Follow-Up

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Running head: Mobility and unmet physical activity need

Abstract

Background: Many older people report willingness to increase outdoor physical activity (PA), but no opportunities for it, a situation termed as unmet PA need. We studied whether lower neighborhood mobility and PA precede the development of unmet PA need.

Methods: Community-dwelling 75-90-year-old people (n=700) were interviewed annually for two years. Unmet PA need, neighborhood mobility and PA were self-reported. Additionally, accelerometer-based step counts were assessed among a subgroup (n=156).

Results: Logistic regression analyses revealed that lower baseline neighborhood mobility (OR 3.02, 95% CI 1.86-4.90 vs. daily) and PA (OR 4.37, CI 2.62-7.29 vs. high) were associated with the development of unmet PA need over two years. Participants with higher step counts had lower risk for unmet PA need (OR 0.68, CI 0.54-0.87).

Conclusion: Maintaining higher PA levels and finding solutions for daily outdoor mobility, especially for those with declines in health, may protect from the development of unmet PA need.

Keywords: Aging, Outdoor mobility, Physical function

Many older people report that they would like to be more physically active but do not have an opportunity for that (Eronen et al., 2014; Rantakokko et al., 2010), which is a situation that is termed unmet physical activity need (Rantakokko et al., 2010). Those experiencing unmet PA need are motivated to increase PA, but may need support in PA participation, and thus, may form a fruitful target group for PA interventions (Rantakokko et al., 2010).

According to previous studies unmet PA need is more common among older people with musculoskeletal diseases and depressive symptoms (Rantakokko et al., 2010), and accumulation of risk factors including lower socioeconomic status, poorer health and mobility limitations increase the risk for the development of unmet PA need (Eronen, von Bonsdorff, Rantakokko, & Rantanen, 2012). An earlier study showed that older people experiencing unmet PA need are more likely to be physically inactive, but inactive older people do not always report unmet PA need (Eronen et al., 2012). Physical inactivity can be defined as not performing sufficient amount of PA i.e. not meeting the respective PA guidelines (Barnes et al., 2012). Unmet PA need describes the willingness and perceived opportunities for PA, not the actual amount of PA, and it is therefore conceptually different from physical inactivity. Furthermore, unmet PA need seems to be more common among those whose PA has recently reduced (Rantakokko et al., 2010). It has been suggested that unmet PA need is transient and older people adjust to lower levels of PA if opportunities for PA participation are not improved (Rantakokko et al., 2010). Many reasons may contribute to older people's perceived opportunities for PA participation including physical limitations, competing interests or difficulties accessing exercise facilities (Franco et al., 2015). The role of PA in the development of unmet PA need remains unclear and studies on whether lower levels of PA predict the development of unmet PA need over time are lacking.

The amount of PA tends to decrease with advancing age (DiPietro, 2001; Schrack et al., 2013). The most popular form of physical activity among older people is walking (Lim & Taylor, 2005). Walking is physical exercise but is also an essential part of transportation in terms that reaching public transportation or car often requires walking at least short distances (Rantanen, 2013). On days that older people stay inside or in the immediate vicinity of their homes, PA level remains low and it starts to increase as people move further away even if they use motorized transportation (Portegijs, Tsai, Rantanen, & Rantakokko, 2015). Previous findings show that going outdoors into the neighborhood at least once a week can help maintaining physical function among frail older people (Shimada et al., 2010), but going outdoors daily increases the probability of positive health outcomes even further (Jacobs et al., 2008).

We studied whether lower levels of self-reported PA, accelerometer-based step counts and lower frequency of neighborhood mobility were associated with the development of unmet PA need over a two-year follow-up period among community-dwelling older people. These assessment methods complemented each other and provided a more comprehensive picture of participants' PA level. Furthermore, we studied whether a recent reduction in PA and frequency of neighborhood mobility were associated with the development of unmet PA need.

Methods

The study is part of a larger two-year prospective cohort study of 75- to 90-year-old community-dwelling older adults conducted between years 2012-2014. Participants were recruited from a random sample (N=2550) drawn from the national population register based on age and place of residence. Of the initial sample, 848 of them were found eligible based on inclusion criteria (willingness to participate, living independently in the recruitment area, ability to communicate) (Rantanen et al., 2012). At baseline, participants were interviewed at their homes. Of them, 816 of them participated in the one-year follow-up and 761 in the two-year follow-up conducted by phone (Rantakokko et al., 2016). In addition, a subgroup (n=174) wore accelerometers for 7 consecutive days at baseline. In the current analyses we included 700 people who did not have unmet PA need at baseline and who had data on unmet PA need at least on one of the follow-ups (accelerometer substudy n=156). The study has been approved by the Ethical Committee of the University of Jyväskylä. All participants were informed about the study and signed a written informed consent.

Unmet PA need

Unmet PA need was assessed at baseline, and one-year and two-year follow-ups with two questions: "Do you feel that you would have the opportunity to increase your level of outdoor PA if someone recommended you do so?" and "Would you like to increase your level of outdoor PA?". The response options were "yes" or "no". Participants, who reported that they wanted to increase their PA level, but perceived no opportunity to do so, at least at one of the follow-ups, were defined as those who developed unmet PA need (Rantakokko et al., 2010). The participants were then categorized into those who had developed unmet PA need over the course of the follow-up and those who had not.

Self-reported PA level

Self-reported level of PA was assessed at baseline and the one-year follow-up with a modified version of a single-item scale (Grimby, 1986). The scale has been validated and found to correlate well with accelerometer-based measures of PA (Portegijs, Sipilä, Viljanen, Rantakokko, & Rantanen, 2017). The scale assesses the frequency and intensity of PA and has seven response options (mostly resting, mostly sitting, light PA, moderate PA about 3 h a week, moderate PA at least 4 h a week or heavier PA up to 4 h per week, engaging in active sports several times a week, participating in competitive sports). Reduction of PA level was assessed between baseline and the one-year follow-up. Those who reported less PA at one-year follow-up than at baseline, were considered to have reduced their PA level (reduced PA level vs. no change or increased PA). For all other analyses PA was categorized into low activity (light PA at most), moderate activity (at most three hours per week of moderate activity) and high activity (at least four hours of moderate activity per week) (Portegijs et al., 2017).

Frequency of neighborhood mobility

Frequency of neighborhood mobility was assessed at baseline and during the follow-up with a question extracted from the University of Alabama at Birmingham Study of Aging Life-Space Assessment (LSA) questionnaire (Baker, Bodner, & Allman, 2003). Participants were asked to report how often they went out into their neighborhood (other than own yard or apartment building) during the past four weeks (daily, 4-6 times per week, 1-3 times per week and less than weekly). Reduction in the frequency of neighborhood mobility was assessed between baseline and the one-year follow-up. Participants, who reported less frequent neighborhood mobility at one-year follow-up than at baseline, were considered to have reduced neighborhood mobility (reduced vs. no change or increased). For all other analyses, response options were categorized into “3 times per week or less”, “4-6 times per week” and “daily”.

Accelerometer-based PA

At baseline, a subgroup of participants wore a tri-axial accelerometer (Hookie AM20 Activity Meter, Hookie Technologies Ltd, Espoo, Finland) on their right hip on their waking hours except when bathing or during other water-related activities for 7 consecutive days following the home interview. They were encouraged to maintain their normal daily routines during the measurement period. Participants were instructed to report their daily accelerometer wear time, including any potential breaks from wearing the accelerometer, into an activity diary (Rantanen et al., 2012).

From the accelerometer data, we used average daily step counts to describe participants' physical activity. We used defaults settings provided by the manufacturer for thresholds and formulas for calculating step counts. Average step counts were then calculated by dividing the total step counts by the number of valid days of measurement. A day was considered valid when at least 10 hours of wear time was reported. Participants who had at least four valid accelerometer days with no more than one day between consecutive valid days of measurement were included in the analyses (Tsai et al., 2016).

Covariates

All covariates were assessed at baseline. Lower extremity performance was measured with the Short Physical Performance Battery (SPPB) (Guralnik et al., 1994) which includes tests of balance, walking speed and chair stands. The scale has a range from 0 to 12 with higher scores indicating better physical performance. Depressive symptoms were measured using the Center for Epidemiologic Studies Depression Scale (CES-D, range 0-60; higher scores indicate more depressive symptoms) (Radloff, 1977). Years of education was self-reported. Number of chronic diseases was self-reported and measured using a list of 22 common chronic diseases (Portegijs, Rantakokko, Mikkola, Viljanen, & Rantanen, 2014). Additional open-ended questions were included where participants could report any other physician diagnosed diseases.

Statistical methods

The participants' baseline characteristics were described using means with standard deviations or percentages. Medians with interquartile ranges were reported for average step counts among the subgroup who wore accelerometers. Group differences between those who developed unmet PA need over the follow-up and those who did not, were tested with Mann-Whitney U test (continuous variables) and chi-square tests (categorical variables). Binary logistic regression analyses were performed to study the associations of baseline mobility and PA variables with the development of unmet PA need over the two-year follow-up. In the analyses, participants with high PA level were set as the reference group. In addition, logistic regression analyses were performed to study whether reductions in self-reported PA and neighborhood mobility were associated with the development of unmet PA need at one- or two-year follow-up. In these analyses, participants who did not have reductions in their level of PA or neighborhood mobility formed the reference group. All models were adjusted first for age and sex, and then SPPB score, CES-D score, number of chronic diseases and years of education were added separately. Finally, a fully adjusted model was formed. In all models that included accelerometer data, accelerometer wear time was adjusted for. Models that included reduction of PA or frequency of neighborhood mobility were additionally adjusted for PA level or frequency of neighborhood mobility at baseline.

The data were analyzed using IBM SPSS Statistics 24 for Windows (IBM Corp, Armonk, NY). The results were considered statistically significant when P-value was <0.050 or when 95% confidence intervals did not include 1.

Results

The baseline characteristics of the participants are presented in Table 1. Participants who developed unmet PA need over follow-up were older ($p=0.002$), more likely to be women ($p=0.020$) and had less years of education ($p=0.007$) when compared to participants without unmet PA need. Furthermore, they were physically less active ($p<0.001$) and had poorer lower extremity function ($p<0.001$), lower frequency of neighborhood mobility ($p<0.001$), more depressive symptoms ($p<0.001$), and more chronic diseases ($p<0.001$).

PA level, frequency of neighborhood mobility, step counts and the development of unmet PA need

Results of logistic regression analyses are presented in table 2. Participants with low baseline PA level had four-fold age- and sex-adjusted odds for developing unmet PA need on the two-year follow-up period when compared to those who engaged in high levels of PA (OR 4.37, 95% CI 2.62-7.29). For participants who engaged in moderate PA at baseline, the age- and sex-adjusted odds for developing unmet PA need over two-year follow-up were nearly double compared to those with high PA levels (OR 1.89, 95% CI 1.10-3.23). After adjusting for other covariates, low PA level (OR 2.41, 95% CI 1.38-4.21), but not moderate (OR 1.62, 95% CI 0.93-2.82), remained statistically significantly associated with the development of unmet PA need (Table 2).

The participants, who went out into the neighborhood 3 times per week or less at baseline, had three-fold odds for the development of unmet PA need compared to those who went out daily, when adjusted for age and sex (OR 3.02, 95% CI 1.86-4.90). When adjusted further for other covariates, the association attenuated (OR 1.67, 95% CI 0.98-2.85). The age- and sex-adjusted odds were nearly double for those who went out into the neighborhood 4-6 times per week at baseline when compared to those who did so daily (OR 1.67, 95% CI 1.05-2.65). However, the association did not remain statistically significant when adjusting further for chronic diseases and depressive symptoms (Table 2).

Among the subgroup who wore accelerometers, the participants who had higher average step counts at baseline had lower odds for the development of unmet PA need over the two-year follow-up period when adjusted for age, sex and average accelerometer wear time (OR 0.68, 95% CI 0.54-0.87 per 1000 step increase). The association remained statistically significant after adjusting further for SPPB score and CES-D score, chronic diseases and years of education (OR 0.74, 95% CI 0.58-0.95, Table 2).

Reductions in PA, neighborhood mobility and the development of unmet PA need

The odds for the development of unmet PA need were three-fold for those who had reduced PA compared to those with no change or an increase when adjusted for age, sex and baseline PA level (OR 3.10, 95% CI 1.79-5.34). The association remained statistically significant after adjusting further for SPPB score, CES-D score, chronic diseases and years of education (OR 2.57, 95% CI 1.46-4.51, Table 2).

For participants who had reduced the frequency of going outdoors into the neighborhood, the odds for the development of unmet PA need were double when adjusted for age, sex and baseline frequency of neighborhood mobility and compared to those with no reduction (OR 2.06, 95% CI 1.31-3.24). The association did not markedly change after adding SPPB score, CES-D score, chronic diseases and years of education into the model (OR 1.95, 95% CI 1.21-3.15).

Discussion

Lower levels of PA, going out into the neighborhood less frequently and lower step count precede the development of unmet PA need. PA is considered a valued activity that can help older people to maintain their health and independence (Franco et al., 2015) as well as support satisfying basic psychological needs (Springer, Lamborn, & Pollard, 2013). The findings expand the current knowledge by providing a more comprehensive picture about the relationship between PA and unmet PA need among community-dwelling older people.

Inactivity is a known risk factor for health decline and thus, it is possible that declines in participants' health explain the observed associations. Although we adjusted the analyses for various health factors, we were only able to account for these at baseline and did not have the possibility to evaluate the severity of the diseases that participants reported. Engaging in PA (Paterson & Warburton, 2010) and daily outdoor mobility (Jacobs et al., 2008) reduce the risk for functional limitations in old age. Low levels of PA can accelerate functional decline and lead to mobility difficulties, a known risk factor for unmet PA need (Eronen et al., 2014). Depressive symptoms are also more likely to be reported by inactive older people (Lindwall, Rennemark, Halling, Berglund, & Hassman, 2007) and are known to coincide with unmet PA need (Rantakokko et al., 2010). Furthermore, older people who are physically less active and go out less frequently may be unaware of opportunities for PA and thus, may be more likely to stay indoors as their health declines.

In line with earlier findings (Rantakokko et al., 2010), the present findings suggest that unmet PA need is more likely to develop for older adults with recently reduced PA level. This indicates that the will to be physically active remains despite decreased level of PA. Decreasing PA participation is often not a choice, but different barriers of PA, including poor health, mobility and environment-related barriers, may appear with advancing age and increase the risk for unmet PA need (Eronen et al., 2014). Furthermore, lower available energy and fatigability are associated with lower PA levels (Schrager, Schrack, Simonsick, & Ferrucci, 2014; Wanigatunga et al., 2018). Lack of energy may hinder older people's opportunities for PA participation, and for many activities the time getting ready and to reach the location may require more time and energy than they are willing to spare (Devereux-Fitzgerald, Powell, & French, 2018). As previously suggested, unmet PA need may be transient and experienced for some time after a reduction of PA (Rantakokko et al., 2010). If opportunities for PA participation are not improved, people may adapt to the situation and the will to be more physically active can be diminished, thus leaving PA levels permanently low. A recent study showed that adopting adaptive walking modifications while walking longer distances, such as using assistive device or stopping to rest, can help maintain outdoor mobility and prevent unmet PA need (Skantz et al., 2019). Encouraging the use of adaptive strategies to continue participation in outdoor PA could help alleviate unmet PA need.

Going outdoors is often a prerequisite for participation in physical activities and for many older people PA accumulates while attending to activities that require going outdoors, such as shopping and walking for exercise (Tsai et al., 2016). We found that lower frequency of neighborhood mobility at baseline was associated with increased odds for the development of unmet PA over the follow-up period. This association was explained by differences in health at baseline. Environmental barriers near the home entrance may hinder older people's opportunities to go outdoors especially among those with declined lower extremity function (Portegijs, Rantakokko, Viljanen, Rantanen, & Iwarsson, 2017). Reducing environmental barriers may help older people with declining physical function to maintain daily outdoor mobility and protect from the development of unmet PA need.

The strengths of the current study include a relatively large population-based sample of community-dwelling older adults and the longitudinal study setting that allowed for a study the development of unmet PA need over time. A further strength was the availability of both self-reported and accelerometer-based PA data. These assessment methods complemented each other and provided a more comprehensive picture of PA level in our study sample. Self-reported PA level captures intensity and frequency of PA, including household chores that may not typically be seen as PA. Frequency of going outdoors into the neighborhood reflects older people's PA, even though it is not perceived as PA per se. Accelerometers provide a more objective way of measuring PA and capture activities that people may have trouble recalling.

The study also has its limitations. First, reduction in self-reported PA and the incidence of unmet PA need was measured at the same time point for 25 participants, and reduction of neighborhood mobility and the incidence of unmet PA need for 29 participants. Although it is probable that the reductions in PA or neighborhood mobility happened prior the development of unmet PA need, we cannot rule out the possibility of this being the other way around. Second, although we adjusted the analyses for chronic diseases, lower extremity performance and depressive symptoms, we were only able to account for these at baseline. Thus, we cannot confirm whether changes in participants' health explain the observed associations. Third, as in many studies targeting the aging population, it is possible that the results are affected by selective mortality which causes changes to the aging cohorts (Zajacova

& Burgard, 2013). The drop-out rate by the second follow-up was 10%, and those with poorer health were more likely to have died or dropped out of the study.

Conclusions

The findings show that older people with relatively inactive lifestyle are at higher risk for developing unmet PA need over time. Thus, providing opportunities and supporting equal opportunities for PA participation is especially important for older people who are physically less active. Similarly, maintaining higher PA levels and finding solutions for maintaining daily outdoor mobility, especially for those with declines in health, may protect from the development of unmet PA need over time. Overall, older adults with unmet PA need form an important target group for PA interventions as they are already motivated to increase their level of PA but may need special support in PA participation. Given the many health benefits of PA, equal opportunities for PA participation should be secured for everyone, despite age and declines in health and function.

Acknowledgments

The Gerontology Research Center is a joint effort between University of Jyväskylä, Finland and University of Tampere, Finland. This work was supported by the Finnish Ministry of Education and Culture (to MR and TR), the Academy of Finland (grant number 255403 to TR), the European Research Council (grant number 693045 to TR) and the University of Jyväskylä. The financial sponsors played no role in the design, execution, analysis or interpretation of data, or writing of the study. The authors declare no conflicts of interest.

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Table 1. Baseline characteristics of the participants according to the development of unmet PA need over the follow-up

	Development of unmet PA need		
	Yes (n=139)	No (n=561)	P-value[a]
	% (f)	% (f)	
Women	69 (96)	58 (327)	**0.020**
PA level			**<0.001**
low	53 (74)	25 (139)	
moderate	28 (39)	32 (180)	
high	19 (26)	43 (242)	
Neighborhood mobility			**<0.001**
3 times or less	36 (50)	18 (98)	
4-6 times	34 (47)	31 (175)	
daily	30 (42)	51 (287)	
	Mean (SD)	Mean (SD)	P-value[b]
Age	81.27 (4.21)	80.04 (4.13)	**0.002**
Years of education	9.10 (4.43)	9.86 (4.18)	**0.007**
Number of chronic diseases	5.20 (2.46)	3.94 (2.26)	**<0.001**
SPPB score	8.60 (2.77)	10.20 (1.94)	**<0.001**
CES-D score	11.83 (7.57)	8.56 (6.14)	**<0.001**
	Development of unmet PA need among accelerometer subgroup		
	Yes (n=34)	No (n=122)	
	Median (IQR)	Median (IQR)	P-value[b]
Average daily step count	1125.50 (1760.55)	2737.07 (3096.05)	**<0.001**

[a]Chi-square test [b]Mann-Whitney U-test

SD=Standard Deviation, IQR=Interquartile Range, CES-D=Center for Epidemiologic Studies Depression Scale, SPPB=Short Physical Performance Battery

Table 2. The association of self-reported PA level, neighborhood mobility and average step counts with the development of unmet PA need over two years among those without unmet PA need at baseline

	Development of Unmet PA need (n=700)					
	Model 1 OR (95% CI)	Model 2 OR (95% CI)	Model 3 OR (95% CI)	Model 4 OR (95% CI)	Model 5 OR (95% CI)	Model 6 OR (95% CI)
Physical activity level						
low vs. high	**4.37 (2.62-7.29)**	**2.81 (1.63-4.86)**	**3.93 (2.34-6.60)**	**3.61 (2.14-6.10)**	**4.27 (2.56-7.14)**	**2.41 (1.38-4.21)**
moderate vs. high	**1.89 (1.10-3.23)**	1.67 (0.97-2.89)	**1.77 (1.03-3.05)**	**1.83 (1.07-3.15)**	**1.89 (1.11-3.25)**	1.62 (0.93-2.82)
Neighborhood mobility						
3 times or less vs. daily	**3.02 (1.86-4.90)**	**1.98 (1.18-3.33)**	**2.68 (1.64-4.37)**	**2.48 (1.51-4.07)**	**2.94 (1.81-4.78)**	1.67 (0.98-2.85)
4-6 times vs. daily	**1.67 (1.05-2.65)**	**1.60 (1.00-2.58)**	1.55 (0.97-2.49)	1.51 (0.94-2.43)	**1.62 (1.02-2.59)**	1.42 (0.87-2.31)
Reduction in PA level vs. no change/increase[a]	**3.10 (1.79-5.34)**	**2.79 (1.60-4.88)**	**2.81 (1.62-4.86)**	**2.95 (1.70-5.11)**	**3.13 (1.81-5.40)**	**2.57 (1.46-4.51)**
Reduction in neighborhood mobility vs. no change/increase[b]	**2.06 (1.31-3.24)**	**1.98 (1.24-3.17)**	**2.02 (1.27-3.20)**	**1.97 (1.24-3.12)**	**2.09 (1.33-3.30)**	**1.95 (1.21-3.15)**
	Development of Unmet PA need among subgroup (n= 152)*					
Average step count[c]	**0.68 (0.54-0.87)**	**0.73 (0.57-0.94)**	**0.69 (0.54-0.88)**	**0.69 (0.54-0.88)**	**0.69 (0.54-0.88)**	**0.74 (0.58-0.95)**

Note. Statistically significant values are bolded. Model 1 adjusted for age and sex, Model 2 adjusted for age, sex and SPPB score, Model 3 adjusted for age, sex and CES-D score, Model 4 adjusted for age, sex and number of chronic diseases, Model 5 adjusted for age, sex and years of education, Model 6 adjusted for age, sex, SPPB score and CES-D score, number of chronic diseases and years of education

[*] OR per 1000 step increase

[a] Adjusted for baseline PA level

[b] Adjusted for baseline frequency of neighborhood mobility

[c] Adjusted for accelerometer wear time