JYU DISSERTATIONS 566

Tiina Savikangas

Physical Activity among Community-dwelling Older Adults

Relationships with Body Composition and Physical Capacity, and the Effects of Physical and Cognitive Training, Multimorbidity Patterns, and Executive Functions

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FACULTY OF SPORT AND HEALTH SCIENCES

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ABSTRACT

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While physical activity has a wide range of benefits for older adults' health and functioning, most older adults are physically inactive. Health status and the cognitive processes required for planned and goal-oriented behavior, known as executive functions, may determine physical activity. This dissertation research investigated the associations of physical activity with body composition and physical capacity in older adults. It also explored the effect of physical and cognitive training on physical activity compared to physical training alone and the impact of executive functions and multimorbidity patterns on the intervention effects.

The data were drawn from a 12-month randomized controlled trial, the PASSWORD study, with follow-ups after one-year and during COVID-19 pandemic. Participants (n=314) were physically inactive 70- to 85-year-old residents of Jyväskylä, Finland. They were randomized to receive either a physical training intervention, including supervised and home-based strength, walking and balance exercises, or the same physical training intervention plus computerized executive functions training. Data were collected by questionnaires, accelerometry, laboratory measurements, and registers.

The results showed that physical activity of any intensity was associated with lower fat percent and faster walking speed, whereas light-intensity activity only was associated positively with bone traits, and the higher intensities only with lower extremity functioning. Physical and cognitive training did not add to the effects on physical activity over physical training alone, whereas higher executive functions at baseline predicted higher physical activity. Physical activity increased in both study groups and was maintained at a higher than baseline level during the follow-up. Multimorbidity patterns had a small impact on physical activity and capacity, while the direction and magnitude of the impact of different chronic conditions varied, with most remaining insignificant.

Thus, even very low-intensity physical activity may be beneficial for older adults, and sustained changes in physical activity can be achieved with multicomponent physical training. While multimorbidity may not substantially impact training outcomes, higher executive functions may facilitate the adoption of a physically active lifestyle.

Keywords: physical activity, exercise, executive functions, multimorbidity

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Savikangas, Tiina
Kotona asuvien iäkkäiden fyysinen aktiivisuus: Yhteydet kehonkoostumukseen ja fyysiseen suorituskykyyn sekä liikunta- ja kognitiivisen harjoittelun, monisairastavuuden ja toiminnanohjauksen vaikutukset
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Fyysinen aktiivisuus edistää iäkkäiden terveyttä ja toimintakykyä, mutta suurin osa iäkkäistä henkilöistä liikkuu terveytensä kannalta liian vähän. Terveydentila ja toiminnanohjaus, eli suunnitelmalliseen ja tavoitteelliseen toimintaan vaaditut kognitiiviset prosessit, voivat määrittää fyysistä aktiivisuutta. Tässä tutkimuksessa selvitettiin fyysisen aktiivisuuden yhteyksiä fyysiseen suorituskykyyn ja kehonkoostumukseen, liikunta- ja kognitiivisen harjoittelun ja pelkän liikunnan vaikutuksia fyysiseen aktiivisuuteen, sekä toiminnanohjauksen ja monisairastavuuden vaikutuksia harjoitusvasteisiin iäkkäillä henkilöillä.

Tutkimuksessa käytettiin PASSWORD-tutkimuksen aineistoa. Tutkimukseen sisältyi 12 kuukauden satunnaistettu kontrolloitu koe, vuoden seuranta-aika ja jatkoseuranta COVID-19 pandemian aikana. Osallistujat (n=314) olivat 70–85-vuotiaita jyväskyläläisiä kotona-asuvia, vähän liikkuvia henkilöitä. Heidät arvottiin liikuntaohjelmaan, joka sisälsi ohjattua ja itsenäistä voima-, kävely- ja tasapainoharjoittelua, tai liikuntaohjelmaan ja tietokoneella toteutettuun kognitiiviseen harjoitteluun. Aineisto perustui kyselyihin, kiihtyvyysmittari- ja laboratoriomittauksiin sekä rekisteritietoihin.

Kaiken tehoinen fyysinen aktiivisuus oli yhteydessä alhaisempaan rasvaprosenttiin sekä suurempaan kävelynopeuteen, mutta vain kevyt aktiivisuus oli positiivisesti yhteydessä reisiluun ominaisuuksiin ja korkeampitehoinen aktiivisuus alavartalon toimintakykyyn. Liikunta- ja kognitiivinen harjoittelu ei lisännyt fyysistä aktiivisuutta enempää kuin pelkkä liikuntaharjoittelu, mutta parempi toiminnanohjaus ennusti korkeampaa fyysistä aktiivisuutta. Fyysinen aktiivisuus lisääntyi kummassakin tutkimusryhmässä ja säilyi alkua korkeampana seurannan aikana. Monisairastavuudella oli hyvin pieni vaikutus fyysiseen aktiivisuuteen ja suorituskykyyn. Eri sairauksien vaikutusten suuruus ja suunta vaihtelivat.

Hyvinkin kevyt fyysinen aktiivisuus voi olla iäkkäiden terveyden ja toimintakyvyn kannalta hyödyllistä. Monimuotoinen liikuntaohjelma voi johtaa pysyviin muutoksiin fyysisessä aktiivisuudessa. Parempi toiminnanohjaus voi edistää fyysisesti aktiivista elämäntapaa, mutta monisairastavuudella ei vaikuttaisi olevan selkeää vaikutusta liikuntaohjelman harjoitusvasteisiin.

Avainsanat: fyysinen aktiivisuus, liikunta, toiminnanohjaus, monisairastavuus

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Jyväskylä 6.10. 2022
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ORIGINAL PUBLICATIONS AND AUTHOR CONTRIBUTION

This thesis is based on the following four original publications, which will be referred to by their Roman numbers. The thesis also includes unpublished results.

I Savikangas, T., Tirkkonen, A., Alen, M., Rantanen, T., Fielding, R. A., Rantalainen, T., & Sipilä, S. (2020). Associations of physical activity in detailed intensity ranges with body composition and physical function. a cross-sectional study among sedentary older adults. *European Review of Aging and Physical Activity*, *17*(1), 1-11. https://doi.org/10.1186/s11556-020-0237-y

II Savikangas, T., Sipilä, S., & Rantalainen, T. (2021). Associations of physical activity intensities, impact intensities and osteogenic index with proximal femur bone traits among sedentary older adults. *Bone*, *143,* 115704. https://doi.org/10.1016/j.bone.2020.115704

III Savikangas, T., Savolainen, T., Tirkkonen, A., Alen, M., Hautala, A.J., Laukkanen, J.A., Rantalainen, T., Törmäkangas, T. & Sipilä, S. The impact of multimorbidity patterns on physical activity and physical capacity among older adults participating in a year-long exercise intervention. Submitted for publication.

IV Savikangas, T., Törmäkangas, T., Tirkkonen, A., Alen, M., Fielding, R. A., Kivipelto, M., Rantalainen, T., Stigsdotter Neely, A. & Sipilä, S. (2021). The effects of a physical and cognitive training intervention vs. physical training alone on older adults' physical activity: A randomized controlled trial with extended follow-up during COVID-19. *PloS One*, *16*(10), e0258559. https://doi.org/10.1371/journal.pone.0258559

As the first author of the original publications, in light of comments from my co-authors, I drafted the study questions and designs, prepared the data for the statistical analyses, and performed the preliminary analyses and part of the final analyses. A statistician was consulted on the more challenging statistical analyses. I assumed the main responsibility for the data interpretation, writing the manuscripts, and all steps in the publication process. I also had an active role in all phases of the data collection in the Promoting safe walking among older people (PASSWORD) study, data from which were utilized in this dissertation.

FIGURES

TABLES

ABBREVIATIONS

ALM	Appendicular lean mass
BL	Baseline measurement
BMC	Bone mineral content
BMD	Bone mineral density
BMI	Body mass index
CC	Chronic conditions
CI	Confidence interval
COVID-19	Coronavirus disease 2019; Extended follow-up during restrictions due to the coronavirus pandemic
DXA	Dual-energy X-ray absorptiometry
EF	Executive function
Est	Estimate
FN	Femoral neck
FU	One-year follow-up
GEE	Generalized estimating equation
HI	High impacts
IQR	Inter-quartile range
LI	Low impacts
LPA	Light-intensity physical activity
MAD	Mean amplitude deviation
MET	Metabolic equivalent of task
MI	Medium impacts
MLLPM	Multinomial logistic longitudinal path model
MMSE	Mini-Mental State Examination
MNW	Minimal neck width
MVPA	Moderate-to-vigorous intensity physical activity
OI	Osteogenic index
PA	Physical activity
PASSWORD	The study *Promoting safe walking among older people*
PT	Physical training group
PTCT	Physical training and cognitive training group
RCT	Randomized controlled trial
SB	Sedentary behavior
SD	Standard deviation
SE	Standard error
SM	Section modulus
SPPB	Short Physical Performance Battery
SRPA	Self-reported current physical activity category
TF	Total femur
TMT	Trail Making Test
WHO	World Health Organization
6m	Measurement at six months
6-min walk	Six-minute walking distance

10-m walk	Maximal walking speed over ten meters
12m	Measurement at twelve months

CONTENTS

1 INTRODUCTION

Life expectancy and, by implication, the number of older adults, is increasing worldwide. While longer lives are a rich resource for individuals and communities, they also challenge health care services and systems (World Health Organization, 2015). These challenges arise from the nature of aging. Aging can be broadly described as a complex process characterized by a progressive, generalized impairment of body functions, which results in an increasing susceptibility to poor health outcomes. Although the rate of aging is influenced by genetic, environmental and incidental factors, a healthy lifestyle can substantially counteract the accumulation of damage and hence loss of function (Kirkwood, 2005). Thus, age-related functional limitations can be delayed. Investing in the health and functioning of aging populations is worthwhile, as the returns are multifold, including individual well-being and active participation in society (World Health Organization, 2015).

One of the key modifiable lifestyle behaviors that can counteract such age-related changes is physical activity (World Health Organization, 2015). In fact, physical activity can have a more profound positive impact on organ systems than any medical treatment (Manini, 2015). Such positive impacts include decelerating the age-related weakening of muscles and bones, while preventing fat gain and loss of physical capacity (Bauman et al., 2016; Piercy et al., 2018). Body composition and physical capacity, in turn, are important predictors of future functioning, morbidity, and mortality (Byrne et al., 2016; Cawthon et al., 2014; Minneci et al., 2015). Therefore, investing in physical activity in old age may bring substantial returns on both the individual and societal levels.

Despite the widely recognized benefits of a physically active lifestyle, insufficient physical activity is a global challenge. In large part, the world's populations are less physically active than would be optimal for the maintenance of good health and functioning (e.g., Bennie & Wiesner, 2021; Hallal et al., 2012). Unfortunately, a declining trend in physical activity has been observed for some considerable time (Conger et al., 2022). The economic and societal burden of low physical activity is high. Up to 8% of all deaths and non-communicable diseases worldwide are attributable to insufficient physical activity, and the burden is even higher in the high-income countries (Guthold et al., 2018). In Finland, the annual costs attributable to low physical activity are estimated to be more than three billion euros, over 10% of which is spent on the institutional care of older people (Kolu et al., 2022). Policies to increase population levels of physical activity must thus be highly prioritized (Guthold et al., 2018). Supporting a physically active lifestyle, particularly in older age, is essential from both the individual and societal perspectives.

Physical training interventions can be effective in increasing physical activity among older adults (Sansano-Nadal et al., 2019). Group-based physical training interventions in particular may be successful since they enable, e.g., social support, perceived health benefits and well-being, and getting up, out and going (Farrance et al., 2016). However, the positive effects of physical training interventions tend to be short-lived and new strategies are needed to foster the long-term maintenance of physical activity (Sansano-Nadal et al., 2019).

It is also important to identify the individual factors that may influence the effectiveness of interventions. One potential determinant is cognitive functioning, especially executive functions. Executive functions are the cognitive processes required for planned and goal-oriented behavior (Alvarez & Emory, 2006). They underlie self-regulation and are thus important for health behavior (P. A. Hall & Fong, 2015). Higher executive functioning may foster compliance with structured training and hence sustained behavior change. Better executive functions also enable behavioral adaptation to changing and challenging circumstances (Collette et al., 2006), such as during the outbreak of the coronavirus disease 2019 (COVID-19). Improving executive functions is thus a potential strategy for promoting and maintaining change in physical activity behavior. While it is generally recognized that physical training can improve executive functions in older adults, combined physical and cognitive training may be even more effective (Malmberg Gavelin et al., 2021).

Another potential determinant of the effectiveness of physical training is health status. Older adults may perceive poor health as a barrier to physical activity; for example, having multiple chronic conditions, i.e., multimorbidity, often results in low physical activity and poor physical capacity (e.g., Ashe et al., 2009; Chudasama et al., 2019; Ryan et al., 2015). Since poor physical capacity predicts future disabilities and mortality, while increased physical activity can diminish the excess mortality risk related to multimorbidity (Chudasama et al., 2019; Martinez-Gomez et al., 2017), it is necessary to develop strategies to increase physical activity and physical capacity in multimorbid older adults. Unfortunately, the little evidence available indicates that interventions aimed at the promotion of physical activity may be less successful in older adults with multimorbidity than in healthier peers (Chase, 2015). Thus, more research is needed to find out if multimorbid older adults can benefit to a similar extent as healthy older adults from physical training.

To extend our understanding of physical activity on the population level, the role of physical activity for health and functioning, and the impact of interventions on physical activity behavior, the accurate assessment of physical activity is crucial (Strath et al., 2012). In the past, physical activity research relied mostly on self-report tools. However, since the beginning of the present century accelerometry has substantially gained in popularity. Nevertheless, the traditional methods of summarizing physical activity in a few simple metrics such as the number of daily minutes in different intensity categories have limited accuracy (Shiroma et al., 2018). For example, the use of standardized thresholds may underestimate physical activity intensity in older adults (Gorman et al., 2014; Strath et al., 2012) and lead to misinterpretation of the relationships between physical activity intensity and health-related outcomes. Averaging physical activity intensity over longer epochs, typically lasting one minute, diminishes the impact of short bursts of high-intensity activity, leaving the potential relationships between high-intensity impacts and bone health largely unobserved (Deere et al., 2016; Vähä-Ypyä, Vasankari, Husu, Suni, et al., 2015). Therefore, novel accelerometer-data processing approaches are required to provide a more comprehensive picture of physical activity, especially in older adults (Shiroma et al., 2018).

This dissertation research used various accelerometer-data processing approaches to yield novel insights on the accumulation of physical activity and the relationships of physical activity with body composition and physical capacity in older adults. A further aim was to investigate whether cognitive training in addition to physical training would provide additive effects over physical training alone on physical activity during and at the end of the intervention, at a one-year follow-up, and during the COVID-19 restrictions. This research project also investigated the influence of multimorbidity patterns and executive functions on the effects of the intervention.

2 REVIEW OF THE LITERATURE

2.1 The concept of physical activity

Physical activity (PA) is defined as any bodily movement that is produced by skeletal muscle and results in substantial energy expenditure over the resting level (Caspersen et al., 1985). PA is complex behavior that varies widely both within and between individuals (Caspersen et al., 1985; Strath et al., 2012). This complexity arises from the domains and dimensions that can be used to classify PA.

The four commonly named domains of PA are occupational, domestic, transportation, and leisure time PA and thus describe the various situations in which PA can occur. Occupational PA covers all work-related PA, such as walking, lifting, and manual labor during work time. Domestic PA includes various activities related to daily living, such as cleaning, cooking, yard work, selfcare, and playing with children or pets. PA related to transportation serves the purpose of getting somewhere, such as walking to the supermarket or bus-stop. Leisure time PA, in turn, comprises recreational and discretionary activities (Strath et al., 2013). Exercise is a subtype of leisure-time PA, which is structured, planned and repetitive in nature, and aims to improve or maintain one or more of the components of physical fitness, including aerobic capacity, muscle strength, balance, and flexibility (Caspersen et al., 1985).

PA can also be classified by dimensions. These include its mode, frequency, duration, and intensity (Strath et al., 2013). Mode refers to the specific type of the activity performed, e.g., walking or cycling. Frequency refers to the number of activity bouts, and duration to the time spent on the activity bout performed, and both can be calculated within a specific time frame, e.g., per day or week. Intensity refers to the rate of energy expenditure during the activity and is an indicator of the metabolic demand of performing the activity (Strath et al., 2013). Activity intensity can be described with multiples of resting energy expenditure, i.e., the metabolic equivalent of the task (MET), and is traditionally categorized as light (1.6 – 2.9 MET), moderate (3.0 – 5.9 MET) and vigorous (⩾6.0 MET) (Ainsworth et al., 2011). Many common domestic activities, such as household walking, preparing food and doing the dishes, fall within the light-intensity physical activity (LPA) category. Moderate-intensity activities include a wide range of activities corresponding to the intensity of brisk walking, gardening, or recreational swimming. Running and aerobics are typical examples of vigorous-intensity activities (Ainsworth et al., 2011). In research, moderate and vigorous activities are often combined to form a single broad intensity category (moderate-to-vigorous intensity physical activity, MVPA). While activities causing energy expenditure above 1.5 times of the resting level are considered as PA, sedentary behavior (SB) is defined as all waking activities performed in a lying, reclining, or sitting position in which energy expenditure is less than 1.5 METs (Tremblay et al., 2017). Typical sedentary activities include watching TV or reading (Ainsworth et al., 2011).

2.2 Health benefits of physical activity in old age

While increasing age is accompanied by declines in health and functioning, these can be counteracted by PA (Bauman et al., 2016). According to the classical model of the disablement process proposed by Verbrugge and Jette (1994), age-related cell-level changes and chronic conditions trigger organ-level dysfunction and structural abnormalities, such as decreasing muscle strength and aerobic capacity. These pathologies and impairments may be modified by various risk factors, including PA and SB. Impairments in specific body sites may, in turn, lead to functional limitations in basic physical actions, such as walking and climbing stairs. Without external or internal interventions, functional limitations may lead further to more generalized disablement, i.e., difficulties in performing activities of daily living (Verbrugge & Jette, 1994). Changing PA behavior is one of the key strategies of interventions aimed at preventing disability and thus supporting older adults' independence (Tak et al., 2013). PA is known to protect against both mobility disability (Pahor et al., 2014) and cognitive decline (Bherer et al., 2013; Northey et al., 2018), both important determinants of capability in performing activities of daily living.

Reduced all-cause and cardiovascular disease mortality risk are probably the most studied outcomes of PA, and recent research has suggested that PA of any intensity substantially lowers mortality risk (Ekelund et al., 2019). An important factor beyond the relationship between higher PA and lower mortality risk is that regular PA counteracts the development and progress of numerous common chronic conditions (Pedersen & Saltin, 2015). For example, PA is recommended as a first-line treatment for the management of high blood glucose, blood pressure and blood cholesterol to delay the progression of more severe cardio-metabolic conditions, including cardio-vascular disease and type II diabetes (Barone Gibbs et al., 2021; Colberg et al., 2016).

PA also contributes to physical health and functioning owing to its beneficial effects on body composition. Regular PA can counteract the accumulation of body fat and loss of skeletal muscle and bone mass that come with increasing age (Benedetti et al., 2018; Distefano & Goodpaster, 2018; Liberman et al., 2017). These co-occurring age-related changes in body composition are accompanied with reduced PA and the development of functional limitations, which together increase the risk of disability, morbidity, and mortality (Zamboni et al., 2008). In addition, age-related bone loss predisposes to fractures, which may limit older adults' independence. PA can counteract not only the deterioration in bone strength but also improve balance and mobility, and thus prevent falls and fall-related fractures (Cosman et al., 2014; Drake et al., 2015). The positive effects of structured PA on other aspects of older adults' physical capacity, including muscle strength and power, aerobic capacity, and walking speed are also widely recognized (Bouaziz et al., 2017; Lai et al., 2018; Van Abbema et al., 2015).

Importantly, the greatest reductions in the risk for mortality, several chronic diseases, and cognitive decline in old age occur when the activity level increases from very inactive to at least low-to-moderately active (Balogun et al., 2021; Barengo et al., 2017; Sofi et al., 2011; Warburton & Bredin, 2017). Although life-long PA is recommended, becoming physically active even in later life may substantially benefit health and functioning. Increasing PA may thus support sedentary older adults' independence and quality of life in their remaining years (Bauman et al., 2016; Manini & Pahor, 2009; McPhee et al., 2016).

2.2.1 Body composition

Body composition can be considered at different levels, from its atomic components to the tissue system and the whole-body. On the tissue-system level, the human body can be divided into muscle, fat, bone, blood, and other tissues (Wang et al., 1992). Body composition at the tissue-system level is commonly assessed using dual-energy X-ray absorptiometry (DXA), a technology that is simple, safe, and precise. DXA has the capability to distinguish between bone mineral and soft tissue and to divide the soft tissue further into fat and lean mass (Laskey, 1996). It should be noted that lean soft tissue includes not only muscle tissue but also other components such as skin and tendons (Müller et al., 2014). DXA-derived fat-free mass, in turn, includes both lean soft tissue and bone mineral mass (Scafoglieri & Clarys, 2018). On the whole-body level, body composition comprises the exterior and physical characteristics of the body. For example, waist circumference, height and weight, and body mass index (BMI, kg/m^2) derived from height and weight are indices of body composition on the whole-body level, often described as anthropometric measures (Madden & Smith, 2016; Wang et al., 1992).

2.2.1.1 Body fat

Fat tissue acts as the main energy storage of the body, but is also important for, e.g., immune and hormone function, thermoregulation, and the mechanical protection of other tissues. Fat tissue is subject to rapid changes as a result of accomodation to energy availability. These changes are accomplished by changes in both the size and number of fat cells (Tchkonia et al., 2010). The amount and distribution of fat tissue changes throughout middle and old age. Both total body fat mass and the relative proportion of body fat, i.e., body fat percent, increase with increasing age (Goodpaster et al., 2006). In general, fat gain is due to excess energy intake compared to total energy expenditure. In old age, this imbalance is usually caused by decreased energy expenditure rather than increased energy intake (Villareal et al., 2005). Both PA energy expenditure and resting energy expenditure decrease with increasing age, and thus contribute to fat gain (Elia et al., 2000). The decrease in resting energy expenditure is partly, but not fully, explained by reduction in fat-free mass (St-Onge & Gallagher, 2010). Several age-related hormonal changes, including decline in growth hormone and testosterone, may also contribute to fat gain (Villareal et al., 2005). Fat gain in older age typically occurs without an increase in body weight. Such fat especially accumulates in the abdominal area and is thus marked by an increased waist circumference (Raguso et al., 2006; St-Onge & Gallagher, 2010). The proportional increase in body fat is greater in men than in women (Goodpaster et al., 2006). It should, however, be noted that the changes in fat accumulation in old age are not linear: fat mass increases up to the age of approximately 70 to 75 years, plateaus, and then begins to decline. It has been suggested that the increase plateaus somewhat earlier among women than men (Westbury et al., 2020).

PA contributes to total energy expenditure and is thus an important behavioral factor in avoiding excessive fat gain. Cross-sectional studies have shown that accelerometer-based total PA and MVPA are inversely and SB positively associated with body fat mass and percent body fat among older adults (Galmes-Panades et al., 2019, 2021; Recio-Rodríguez et al., 2017; Sabia et al., 2015; Westbury et al., 2018). In contrast, studies on the associations between LPA and body fat are scarce, although preliminary evidence indicates that substituting SB with LPA may be associated with lower body fat mass and percentage (Galmes-Panades et al., 2021). Habitual low-intensity activities contribute substantially to higher energy expenditure among older adults, and may therefore be important in counteracting the age-related accumulation of fat mass (Füzéki et al., 2017). This is supported by the inverse relationship between LPA and proxy measures of body fat, such as waist circumference and BMI, among older adults (Bann et al., 2015; Loprinzi et al., 2015).

Structured exercise may be an effective measure to avoid excess fat gain and reduce body fat. Consistent evidence shows that various types of physical training interventions, including resistance, aerobic and combined exercise, are effective in reducing fat mass and percent body fat among older adults (Bouaziz et al., 2017; N. Chen et al., 2021; Liberman et al., 2017). Excessive fat gain, i.e., obesity, can exacerbate physical limitations in old age. PA is considered to be an important lifestyle treatment for obesity among older adults, as it may not only lead to increased energy expenditure and thus to decreased body fat, but also improve physical functioning in obese individuals (Villareal et al., 2005).

2.2.1.2 Skeletal muscle

Skeletal muscle tissue is crucial for mobility and metabolic regulation and is thus of major importance for health (Lang et al., 2010). Driven by age-related physiological and behavioral changes, skeletal muscle mass and function deteriorate. The physiological determinants of muscle loss include neuronal loss, changes in hormone levels and sensitivity, mitochondrial dysfunction, and altered protein metabolism, whereas lifestyle factors include inadequate nutrition and disuse of muscle tissue, i.e., physical inactivity (Cruz-Jentoft et al., 2010; T. N. Kim & Choi, 2013; Lang et al., 2010). These changes result not only in decreased muscle cell number and size but also in deterioration of muscle quality. For example, fat infiltration is accumulated within and between muscles, and the loss of type II fast-twitch muscle cells accelerates more with increasing age compared to the loss of type I slow-twitch muscle cells. Furthermore, type II muscle cells are prone to fiber atrophy, i.e., the size of the muscle cells diminishes (Lang et al., 2010). This progressive age-related decline in muscle mass and quality leads to decreased strength and functioning, especially in tasks requiring the rapid production of force such as rising from seated position (Landi et al., 2014; Lang et al., 2010; Skelton et al., 1994).

Accurate assessment of skeletal muscle mass and quality is costly and restricted by the availability of imaging technologies such as computed tomography and magnetic resonance imaging. Lean mass is often used as a proxy measure for skeletal muscle mass in research, owing to its lower cost and the wider availability of measurement technologies such as DXA (Heymsfield et al., 2015; Scafoglieri & Clarys, 2018). Skeletal muscle comprises the largest fraction of lean mass, especially in the limbs. Appendicular lean mass (ALM), the sum of lean mass in the arms and legs, provides thus a good estimate of skeletal muscle (J. Kim et al., 2002). Both total lean mass and ALM decrease significantly with increasing age, indicating a decrease in skeletal muscle mass, even when a stable weight is maintained (Goodpaster et al., 2006; Raguso et al., 2006; Westbury et al., 2020).

Skeletal muscle tissue adapts to loading (Cartee et al., 2016). Hence, PA and exercise have the potential to counteract the age-related loss of skeletal muscle via several pathways, including increased protein synthesis, reduced fat infiltration in muscle tissue, and improvements in vascular and neural function (Distefano & Goodpaster, 2018). While several cross-sectional and longitudinal studies suggest that both total PA and MVPA are positively associated with the maintenance of lean mass in older age (Galmes-Panades et al., 2019, 2021; Sánchez-Sánchez et al., 2019; Scott et al., 2021; Shephard et al., 2013), this has not been supported by other studies (Westbury et al., 2018). Moreover, the evidence on the associations of LPA and SB with lean mass in older adults is mixed. A recent study found that LPA was positively and SB negatively associated with lean mass (Galmes-Panades et al., 2019), although significant associations have not been observed in other studies (Sánchez-Sánchez et al., 2019; Scott et al., 2021). However, lean mass increased when SB or LPA was replaced with MVPA (Galmes-Panades et al., 2021; Sánchez-Sánchez et al., 2019).

The evidence on the effects of exercise interventions on skeletal muscle in old age is inconsistent (Distefano & Goodpaster, 2018). Two recent meta-analyses concluded that physical training or resistance training do not induce significant improvent in different measures of muscle and lean mass among older adults (N. Chen et al., 2021; Lai et al., 2018). However, the effectiveness of physical training on skeletal muscle mass may vary according to the design of the intervention and characteristics of the participant. Resistance exercise is more effective in improving muscle mass than aerobic exercise (Landi et al., 2014), and training with heavy loads may be required to increase muscle mass (Csapo & Alegre, 2016). Furthermore, exercise of various types – resistance, aerobic and combined – may improve muscle mass in healthy but not in frail older adults (Liberman et al., 2017). It must also be recognized that the adaptability of skeletal muscle diminishes in very advanced age and that exercise-induced muscle mass gain declines with increasing age (Cartee et al., 2016). Despite these findings, a physically active lifestyle is thought to attenuate the age-related deterioration of muscle mass and counteract the detrimental effects of a sedentary lifestyle on skeletal muscle (Cartee et al., 2016; Distefano & Goodpaster, 2018).

2.2.1.3 Bone

During adult age, bone mass and strength are maintained by bone remodeling, a process of interplay between osteoclast cells removing old bone and osteoblast cells replacing the removed bone with new tissue (Manolagas, 2000). However, bone mineral content (BMC) and bone mineral density (BMD) decrease with aging due to imbalance in bone resorption and formation. Trabecular bone loss begins already from as early as the third decade of life, whereas cortical bone is highly maintained until middle age in women and until older age in men (Riggs et al., 2004, 2008). In women, rapid bone loss occurs during the perimenopause and early menopausal transition due to a decline in estrogen concentrations, and overall bone loss is therefore greater in women than in men (Drake et al., 2015; Riggs et al., 2004, 2008). In old age, bones also become weaker due to changes in their morphology. For example, the outer diameter of long bones such as the femur increases while the cortical bone layer thins, processes which negatively affect BMD (Boskey & Coleman, 2010). In adults aged 70 and older, the decline in hip BMD is approximately 0.5% per year but accelerates with increasing age (Westbury et al., 2020). The acceleration of normal age-related bone loss may have various secondary causes, including medications and chronic conditions (Drake et al., 2015).

PA is a key determinant of bone strength. Mechanical loading during PA strains bone, creating signals that initiate biological reactions to the loading that lead to bone adaptations (Frost, 1994). Muscle strength influences the magnitude of bone loading, and hence decreased muscle mass and strength lead to weaker contractions and less loading capacity (Robling, 2009). Two types of PA are typically considered as bone strengthening: weight-bearing impact activities and muscle strengthening activities. Weight bearing is defined as any activity in which the arms, legs and/or feet bear the weight, e.g., jogging, dancing, and tennis. In strength and/or resistance activities, the joints are working against some external resistance, such as generated by resistance machines or resistance bands (Benedetti et al., 2018). For older adults, both regular weight-bearing and muscle strengthening PA are recommended to maintain or improve bone strength (Cosman et al., 2014). The bone-strengthening effects of PA are highly site-specific, since improvements occur only in the stimulated body regions. Therefore, not all exercise regimens can improve bone properties in the crucial regions, including the femoral neck and the spine (Benedetti et al., 2018; Marques et al., 2012).

It has been proposed that PA needs to deviate from habitual activity and to be dynamic in nature to promote bone health; however, even short bursts of abnormal and dynamic activity may be osteogenic (Turner & Robling, 2005). The evidence on the relationship between daily PA and bone health in older age is limited and somewhat inconsistent. Some studies have not shown any significant associations between PA of any intensity and bone traits (Gába et al., 2012; Gerdhem et al., 2008). Other studies have shown a positive association between MVPA and several weight-bearing bone properties, but not between LPA and bone traits (Johansson et al., 2015; Langsetmo et al., 2020). Similarly, SB has been inversely associated with BMD in some studies (Braun et al., 2017) but not in others (Gába et al., 2012). It should be noted that the traditional measures, in which PA intensity is averaged over a given epoch, such as one minute, do not adequately capture short and sporadic bouts of potentially osteogenic dynamic activity (Deere et al., 2016; Vähä-Ypyä, Vasankari, Husu, Suni, et al., 2015). The few studies that have investigated the association of impact counts or impact-based summary scores with bone traits in the general adult population suggest that high impact exercises corresponding to the impact intensity of vertical jumps or running are associated with better bone health (Ahola et al., 2010; Vainionpää et al., 2006). However, while impacts of such high intensity are very rare in older adults (Hannam, Deere, Hartley, Clark, et al., 2017; Tobias, 2014), it has been proposed that in older, compared to younger adults, lower intensity impacts are associated with bone density (Hannam, Deere, Hartley, Al-Sari, et al., 2017; Stiles et al., 2017).

Exercise can decelerate age-related bone loss and even improve bone strength in older adults, especially when it includes a high dose of PA and resistance training or multiple types of exercises (Benedetti et al., 2018; Pinheiro et al., 2020). The combination of resistance training with high-impact activity may be the most beneficial form of exercise as mechanical loading stimulus creates sufficient strain magnitudes and rates and deviates from habitual activity in its loading pattern (Marques et al., 2012). Resistance training with heavy loads may also be beneficial for bone health as a single training modality (Gomez-Cabello et al., 2012; Marques et al., 2012; Pinheiro et al., 2020). In addition, weight-bearing exercise types may somewhat attenuate the loss of bone in osteoporotic individuals (Benedetti et al., 2018). However, walking alone generates only a modest mechanical loading on the bones and thus may not be intense enough to improve bone strength in older age (Gomez-Cabello et al., 2012). It may, however, contribute to the maintenance of bone density. It has also been suggested that long-term walking interventions lead to modest improvements in hip BMD among previously sedentary postmenopausal women (D. Ma et al., 2013; Martyn-St James & Carroll, 2008). Research on the effects of very high-impact activities, such as vertical jumping and running protocols, on older adults' bone health is lacking, as an exercise regimen of this kind may not be feasible or safe for most older adults (Marques et al., 2012). There is, however, preliminary evidence showing that bones are adaptive to high-intensity impact training in old age, at least among master athletes who are habituated to lifelong intense exercising (Suominen et al., 2021).

2.2.2 Physical capacity

Age-related physiological changes, especially in the cardiovascular and musculoskeletal systems, lead to decreased physical capacity in such parameters as muscle strength, endurance and postural balance (Manini & Pahor, 2009). These capacities are crucial for maintaining older adults' physical functioning and ability to carry out the activities of daily living (Kasper et al., 2017). In this dissertation, capacity is understood as an individual's ability to perform a specific task in a standardized environment, such as a research setting (World Health Organization, 2001).

Declines occur in several capacities, including muscle strength and power, aerobic capacity and endurance, postural balance, and walking (Fleg et al., 2005; Goodpaster et al., 2006; Milanović et al., 2013; Skelton et al., 1994), and the rate of decline in general accelerates starting around the seventh decade (Ferrucci et al., 2016). Even though age-related deterioration of physical capacity is associated with concurrent deterioration of body composition, the proportional decreases in strength, aerobic capacity and walking speed are notably greater than decrease in muscle mass and increase in body fat (Fleg et al., 2005; Goodpaster et al., 2006; Westbury et al., 2020). In old age, muscle power is lost even faster than muscle strength (Skelton et al., 1994). Decreased muscle strength and power are explained only partly by the loss of muscle mass. Another important factor is decline in neural control, since poorer neural activation leads to a reduction in the amount and speed of maximal voluntary force production (Clark & Manini, 2008). The loss of aerobic capacity, in turn, is influenced by changes in the structure and functions of the cardiovascular system, such as decreased stroke volume and maximal heart rate, and increased arterial stiffening (Ogawa et al., 1992; Thijssen et al., 2016). While the loss of aerobic capacity is independent of the level of PA, those who are highly active maintain higher aerobic capacity throughout their later years than less active peers (Fleg et al., 2005). The decline in both muscular strength and aerobic capacity has been shown to be steeper in men than in women (Fleg et al., 2005; Goodpaster et al., 2006).

The postural control and gait parameters that are important for walking ability also deteriorate with increasing age (J. Gill et al., 2001; Samson et al., 2001; Winter et al., 1990). In addition to changes in musculoskeletal and cardiovascular systems, neurological changes, such as increased reaction time, decreased visual acuity, and weakened somatosensory systems, affect walking in older adults (F. Prince et al., 1997). Furthermore, factors related to gait pattern, such as shortening of stride length, contribute to the slowing of walking speed (F. Prince et al., 1997; Samson et al., 2001; Winter et al., 1990). Age-related deterioration also occurs in the vestibular system, affecting postural balance and, hence, walking safety (Allen et al., 2017). Both standing and dynamic balance deteriorate in old age, manifested in, e.g., increased body sway during various stance and gait tasks and decreased one-legged stance time (J. Gill et al., 2001). Older adults may also slow their walking speed as a coping strategy to increase walking safety in balance-challenging circumstances, such as when the walking surface is altered or sensory support is diminished (J. Gill et al., 2001).

Although age-related declines in physiological systems are to some extent unavoidable (Manini & Pahor, 2009), regular PA is known to contribute substantially to the maintenance of physical capacity in old age (Paterson & Warburton, 2010). PA improves physical capacity through several pathways. For example, adaptations to PA in the neuromuscular system lead to better coordination of movement, adaptations in the cardiopulmonary system help to distribute oxygen and nutrients more efficiently in the body, and adaptations in metabolic processes improve, in particular, glucose regulation and fatty acid metabolism. Combined, these adaptations help individuals to maintain their physical capacity (McPhee et al., 2016).

In cross-sectional studies conducted among older adults, MVPA has consistently been associated with various components of physical capacity, including aerobic endurance, muscle strength and power, walking speed, and balance (Edholm et al., 2019; Izawa et al., 2017; Jantunen et al., 2016; Lerma et al., 2018; Ramsey, Rojer, et al., 2021; Sánchez-Sánchez et al., 2019; Westbury et al., 2018; Yasunaga et al., 2017), although a few studies have found no relationship between MVPA and muscle strength or walking speed (Gerdhem et al., 2008; Westbury et al., 2018; Yasunaga et al., 2017). In contrast, the evidence on the relationship of LPA with physical capacity is more mixed. Some studies have shown no significant associations of LPA with physical capacity measures (Edholm et al., 2019; Yasunaga et al., 2017), whereas others have found a positive relationship between LPA and several aspects of physical capacity (Jantunen et al., 2016) or only walking-related outcomes (Gerdhem et al., 2008; Lerma et al., 2018). Some studies have observed a significant positive association between LPA and physical capacity in men only (Bann et al., 2015) or in women only (Izawa et al., 2017). According to a recent meta-analysis, LPA is positively associated with muscle strength and power, especially in the lower body (Ramsey, Meskers, et al., 2021). Findings on the association between SB and physical capacity are similarly mixed. According to the meta-analysis of Ramsey and colleagues, SB is inversely associated with lower body muscle strength and power in older adults (Ramsey, Meskers, et al., 2021). A recent systematic review suggested a more general inverse relationship between SB and physical capacity (Mañas et al., 2017), although several studies have found no significant relationships between SB and various measures of physical capacity (Bann et al., 2015; Edholm et al., 2019; Yasunaga et al., 2017).

There is strong evidence showing that aerobic, strength, and multicomponent physical training are beneficial for physical capacity in older adults (DiPietro et al., 2019). Both resistance and aerobic exercise, alone or combined, improve walking speed, endurance, muscle strength and power, and performance in composite tests (Bouaziz et al., 2017; Chase et al., 2017; N. Chen et al., 2021; Lai et al., 2018; Liberman et al., 2017; Liu & Latham, 2009; Van Abbema et al., 2015). However, some aspects of physical capacity can be most effectively improved with specific training modalities. Aerobic exercise induces greater increases in aerobic capacity, whereas resistance training is more effective in improving muscle strength (Landi et al., 2014). Resistance training with both low to moderate and heavy loads leads to significant improvements in muscle strength and related functional outcomes, while high intensity training is superior in improving maximal strength (Steib et al., 2010). Power training, which emphasizes the velocity of movement, is considered to be superior to traditional resistance training in improving muscle power and related functional outcomes, such as walking speed and chair-stand performance (Byrne et al., 2016; Steib et al., 2010). Targeted balance training, in turn, can improve performance in separate balance tasks as well as in test batteries targeting various aspects of balance in different conditions (Lesinski et al., 2015). Among community-dwelling older adults able to attend physical training interventions, the beneficial effects of physical training on physical capacity seem to be greater in frail than non-frail people (Chase et al., 2017). Furthermore, those with poorer baseline physical capacity may show the greatest improvements (Layne et al., 2017). It should, however, be noted that severe mobility difficulties may hinder the planned performance of exercises as and thus also the ability to improve physical capacity (Sipilä et al., 2016; Turunen et al., 2020).

2.3 Assessment of physical activity

Accurate assessment of PA in a free-living environment is crucial to increase our understanding on the population levels of PA and to determine the relationship of PA with health, disease, and disability. Furthermore, reliable and valid assessment of PA is needed to investigate the efficacy of interventions aimed at increasing PA (Strath et al., 2012). PA assessment tools can be divided into two broad categories: self-report methods and device-based measurement tools. Self-reported PA assessment methods can be further divided into questionnaires, logs, and diaries (Ainsworth et al., 2015; Strath et al., 2013). Device-based PA measurement tools include wearable devices assessing physiological responses and movement of the body, such as heart rate monitors, pedometers, accelerometers, and methods combining more than one type of sensor (Ainsworth et al., 2015). Indirect calorimetry and doubly labeled water methods, in which cardiopulmonary properties, oxygen consumption and carbon dioxide production are measured, are the golden standard to assess PA energy expenditure, but costly and not viable for use in large-scale studies (Strath et al., 2013; Yang & Hsu, 2010). It is important to recognize that different device-based PA assessment methods measure different and usually relatively narrow aspects of PA. For example, accelerometers capture movement of the body as accelerations, i.e., mechanical work, while oxygen uptake assessed by e.g., indirect calorimetry, captures the energy cost of this work (Arvidsson et al., 2019). Of the device-based measures, this dissertation focuses on accelerometer-based PA assessment.

In PA research among older adults, it is important to bear in mind that both age and functional status affect the energy cost of PA (Strath et al., 2012). For example, the intensity of walking at a speed of 4.5 km/h is considered to be the equivalent of 3.5 METs, which is moderate according to the Compendium of Physical Activities (Ainsworth et al., 2011). While the absolute intensity of the activity is the same irrespective of the individual's age or fitness level, the relative intensity for a frail older adult with maximum capacity of 6 METs may be vigorous whereas for a young, high-fit adult with a maximum capacity of 12 METs it may be light (Strath et al., 2012). The energy cost of different walking activities from very slow to fast are notably higher in older adults than the reference MET values (K. S. Hall et al., 2013). In general, both motion trackers and questionnaires vary widely in their ability to estimate energy expenditure at both the group and individual levels compared to doubly labeled water (Neilson et al., 2008; Plasqui & Westerterp, 2007). They are, however, more suitable for use in large scale studies and to assess other aspects of PA (Strath et al., 2013). Optimally, several assessment tools are utilized to provide a holistic picture of PA (Nigg et al., 2020; Sattler et al., 2021).

2.3.1 Self-reported physical activity

Different self-reported PA assessment tools are used for different purposes. For example, three main types of questionnaires can be identified: 1) global questionnaires with one to four questions that assess the overall PA status of an individual; 2) short-term recall questionnaires that are used to estimate the total volume of PA and include questions about frequency, duration, and intensity of specific PA types during the past week or month; and 3) quantitative history recall questionnaires used especially in epidemiological studies, including detailed questions about frequency, duration and intensity of specific activities within one or more PA domains over the past month or year or during the lifetime. On the other hand, logs and diaries are used to collect detailed, e.g., hour-by-hour or activity-specific, information about PA behaviors, and are often used in adjunct to device-based measurement of PA (Ainsworth et al., 2015; Strath et al., 2013). In general, self-report tools are the primary measure to assess a person's perceptions of their PA and useful in collecting detailed data on, e.g., specific PA types or domains (Sattler et al., 2021). In addition, self-reports are a valuable tool in longitudinal studies for which device-based measurement of PA is not available at all the timepoints of interest (Metcalf et al., 2018). The advantages of questionnaires are that they can be applied in large samples and are easy, inexpensive, and have a low participant burden (Strath et al., 2013). The main concerns regarding the reliability and validity of self-report measures are their susceptibility to recall and reporting bias, and their low validity for assessing low-intensity and incidental PA (Ainsworth et al., 2015; Kapteyn et al., 2018; Nigg et al., 2020; Strath et al., 2013).

In clinical practice, quick and simple PA assessment tools such as global questionnaires are useful, since they are easy to use and can provide immediate feedback on an individual's general activity level (Nigg et al., 2020). A global questionnaire may, for example, be used to evaluate participant's initial PA level and screen for inclusion criteria in a research project with a single question. Global questionnaires are also feasible with large sample sizes or limited resources and when more complex methods would increase the participation burden (D. P. Gill et al., 2012). In addition, they can focus on the PA domain or type of interest, such as leisure time PA (Ainsworth et al., 2015).

On the other hand, one obvious limitation of short global questionnaires is that they are unable to cover all PA dimensions and domains in detail (Kowalski et al., 2012). They are also limited as a way of assessing compliance with PA guidelines, and in establishing dose–response relationships with other outcomes (Ainsworth et al., 2015). Another possible pitfall in the use of a global questionnaire to assess PA levels is that people from different socio-demographic groups may have different reporting standards and understand their level of PA differently. People may evaluate their activity compared to others in a specific reference group, meaning that global questionnaires relying on individuals' understanding, for example about what counts as moderately active, are not very suitable for comparing PA levels across e.g., countries or age groups (Kapteyn et al., 2018). They may, however, be useful for assessing perceived activity intensity, which allows individuals to relate their activity intensity to their personal physical fitness level (Kowalski et al., 2012). While one-item global questionnaires are relatively simple, their validity and test-retest reliability are modest (D. P. Gill et al., 2012; Hyvärinen et al., 2019). However, change in PA behavior (Hirvensalo et al., 1998) and differences in change by group during a physical training intervention can be detected with such questionnaires (Turunen et al., 2017).

2.3.2 Accelerometer-based physical activity

Accelerometers are small devices that record human movement as body accelerations and decelerations in one to three dimensions. The movements are recorded in gravitational units ($1\ g = 9.8\ m/s^2$), and the raw acceleration data are then processed and transformed into other units to estimate PA volume and intensity over time (K. Y. Chen & Bassett, 2005; Strath et al., 2013; Yang & Hsu, 2010). Counts are the most traditionally used units, although arbitrary and not universal, since the unit is dependent of the manufacturer's signal processing algorithm (K. Y. Chen & Bassett, 2005). In recent years, novel and more transparent raw acceleration data processing approaches have been developed, including Euclidian norm minus one and mean amplitude deviation (MAD) (Arvidsson et al., 2019), which is utilized in the present thesis. MADs are based on actual g units and are independent of the manufacturer brand (Vähä-Ypyä, Vasankari, Husu, Mänttäri, et al., 2015; Vähä-Ypyä, Vasankari, Husu, Suni, et al., 2015). In addition to intensity-based approaches, algorithms have been developed to detect posture and activity type from raw acceleration data (Arvidsson et al., 2019). After processing the raw acceleration data into chosen units, PA data are then further processed and presented as various outcomes, such as mean daily minutes or the proportion of the wear time in intensity categories, mean daily MET, or step count (Arvidsson et al., 2019).

Accelerometer-assessed PA is typically divided into intensity categories, i.e., SB, LPA, and MVPA, based on thresholds derived from validation studies (K. Y. Chen & Bassett, 2005). Validation studies are often performed in children or young adults, but the same cut-offs are also applied in research among older adults (Gorman et al., 2014; Schrack et al., 2016). In count-based approaches, a variety of cut-offs have been used to measure older adults PA. The choice of cut-off may have a significant impact on the results. For example, the amount of MVPA varied from 4 to 80 minutes per day, when eight different cut-offs for MVPA found in the literature were applied to accelerometer recordings of older women (Gorman et al., 2014). The MAD-based cut-offs have been validated against measured oxygen uptake in young adults and adolescents (Aittasalo et al., 2015; Vähä-Ypyä, Vasankari, Husu, Mänttäri, et al., 2015; Vähä-Ypyä, Vasankari, Husu, Suni, et al., 2015) but not among older adults. In a general adult population, MAD-based data processing has shown slightly more SB, but notably lower amounts of LPA and higher amounts of MVPA compared to count-based activity utilizing the most common cut-offs for counts (Leinonen et al., 2017). In research among older adults, it must be recognized that the generally validated intensity category thresholds do not take the individual's fitness level or even age-related decline in fitness into consideration, and hence the cut-offs for light, moderate, and vigorous activity may need to be lower in older adults than in young adults (K. S. Hall et al., 2013).

Although accelerometer-data are traditionally processed and presented in a few simple metrics, such as mean daily minutes of MVPA, by providing opportunities to investigate PA in much more detail they make possible a more comprehensive understanding of PA (Shiroma et al., 2018). In recent years, more advanced analytical methods have been developed, including metrics describing. e.g., activity intensity distribution across the intensity range and activity accumulation patterns. Investigating PA throughout the intensity range has the major strength that the method is independent of PA intensity-category cut-offs (Backes et al., 2022). The traditional intensity-category based metrics are not optimal for assessing bone-loading PA either, since short bursts of high-impact activity may be osteogenic but attenuated when calculating the mean PA intensity in a given epoch, typically 15-60 seconds (Deere et al., 2016). Accelerometer-data processing approaches based on defining the intensity and volume of single acceleration peaks may therefore be useful in assessing bone-loading PA. Acceleration peaks can be either classified and counted as the volume of impacts of specific intensities (Deere et al., 2016; Hannam, Deere, Hartley, Clark, et al., 2017; Vainionpää et al., 2006) or used to calculate a daily sum score such as an osteogenic index (Ahola et al., 2010).

Probably the chief advantage compared to self-reports is that accelerometers can capture a wider range of PA intensities than self-reports, which typically underestimate lighter intensity activities that are hard to recall (Lee & Shiroma, 2014; Schrack et al., 2016). Accelerometers are also easy to use, relatively inexpensive, of small size, noninvasive, and do not disturb normal movements during daily activities. Accelerometers can also assess PA intensity reliably in many ambulatory activities, especially in level walking (K. Y. Chen & Bassett, 2005). However, they have a limited ability to detect PA type (Kowalski et al., 2012). Further limitations include the mischaracterization of nonimpact PA, such as swimming, cycling, and strength training (Schrack et al., 2016), or inability to detect the extra energy cost caused by external loads, such as carrying or pulling something. Choice of body site to attach the accelerometer is of importance in research, since data recorded from different body sites are not directly comparable (Arvidsson et al., 2019). Sensors attached to one body site may fail to correctly capture activity in another part of the body, e.g., hip-worn devices do not accurately record upper-body movement (K. Y. Chen & Bassett, 2005; Lee & Shiroma, 2014). Waist-worn accelerometers are suggested to providea a fair characterization of PA and estimate energy expenditure more accurately than wrist-worn devices (Arvidsson et al., 2019; Yang & Hsu, 2010). Placing the accelerometer at waist-level benefits from the closeness to the center of mass of the whole body. The trunk bears most of the body mass and moves with most activities, and hence the accelerations measured better represent major human motion than the corresponding data from, e.g., wrist- or ankle-worn sensors (Yang & Hsu, 2010). A potential limitation of wrist-worn accelerometers is that they may misclassify sedentary activity that includes upper limb movement as LPA (Arvidsson et al., 2019). The thigh is a less frequent body site for accelerometer placement than the hip or wrist, but is useful for posture detection as it enables measurement of the static inclination of the thigh (Arvidsson et al., 2019).

2.3.3 The relationships between self-reported and accelerometer-based physical activity

In general, self-reported and accelerometer-based SB and PA show small to moderate correlations in general adult populations (S. A. Prince et al., 2008, 2020; Skender et al., 2016). Among older adults, the relationship between accelerometer-based PA and self-reported PA derived from questionnaires ranges from weak to moderate (Skender et al., 2016). The amount of self-reported PA is typically higher than the amount of accelerometer-based PA in general adult populations, whereas self-reported SB is typically lower than device-based SB (S. A. Prince et al., 2008, 2020). Among older adults, some studies have shown higher self-reported than accelerometer-assessed PA and others higher accelerometer-based than self-reported PA, with no clear trend towards either over- or underestimating PA (Domingos et al., 2021; Dyrstad et al., 2014; S. A. Prince et al., 2008).

There are several explanations for the discrepancies between self-reported and accelerometer-based PA. First, self-reports and accelerometers capture different aspects of PA. Accelerometers measure accelerations during all movement and the intensity of PA is based on laboratory-derived thresholds. In contrast, questionnaires reflect the individual's perceived intensity and amount of PA. Hence, the lack of agreement between self-reported and accelerometer-based PA may be explained by misinterpretations of intensity and, in the case of self-reports, respondents' difficulties in remembering the frequency and duration of habitual activities (Ferrari et al., 2020). The risk of recall bias is of special concern in PA research among older adults, since recalling habitual PA is a challenging cognitive task, especially in older age, when impairments in memory and recall skill are common (Lohne-Seiler et al., 2014). Social desirability is another potential source of bias when utilizing self-report tools, i.e., people tend to respond in a way that presents them in good light, which can lead to overreporting of PA (Adams et al., 2005).

Several methodological choices may impact on the level of agreement between self-reported and accelerometer-based PA, such as the accelerometry procedures and self-report tools utilized (Domingos et al., 2021; S. A. Prince et al., 2020; Shiroma et al., 2015). For example, the choice of accelerometer-based MVPA cut-off may impact on the level of agreement with self-reported MVPA (Shiroma et al., 2015). On the other hand, the wording used in PA questionnaires may affect agreement, e.g., whether moderate-intensity PA is described as activities resulting in a slight increase in the breathing or heart rate or illustrated with examples of types of PA such as brisk walking. Furthermore, the tendency to provide socially desirable responses may be stronger when using interviewer-administered tools compared to self-administered questionnaires (Booth, 2000).

Individual factors may also impact on the agreement between different measures. For example, the results of a large systematic review suggest that, compared to men, women tend to self-report more PA than that measured by accelerometry (S. A. Prince et al., 2008). In a large British cohort study, higher socio-economic status was positively associated with a higher correlation between self-reported and accelerometer-based PA in older adults, while other socio-demographic factors did not affect the association (Sabia et al., 2014). A three-country study found that whereas self-reported PA based on a global questionnaire did not differ between English, Dutch, and American participants, the English and Dutch respondents recorded more accelerometer-based activity than their American counterparts. Furthermore, it was observed that self-reported PA did not vary by age, whereas accelerometer-based PA declined with increasing age, indicating that age and country had an impact on the agreement between self-reported and accelerometer-based PA (Kapteyn et al., 2018). One explanation to this may be that understanding of concepts like *physical activity* or *exercise* or other wordings utlized in the PA questionnaires may vary not only between countries but also between different populations within the same country (Booth, 2000). Personality traits, which are relatively stable tendencies in feeling, thinking and behaving, may also play a role in reporting one's PA behavior and thus influence the level of agreement between self-reported and accelerometer-based PA (Kekäläinen et al., 2020).

2.4 Physical activity in old age

2.4.1 Physical activity recommendations for older adults

The Physical Activity Guidelines for Americans and the World Health Organization (WHO) global guidelines for physical activity both recommend that all adults, including older adults, engage in 150–300 minutes of moderate intensity or 75–150 minutes of vigorous intensity aerobic activity, or an equivalent combination of moderate and vigorous intensity activity, per week. Accumulating MVPA beyond the recommended level may bring additional health benefits. In addition, both guidelines include a recommendation to perform muscle strengthening activities of at least moderate intensity at least twice per week (Bull et al., 2020; Piercy et al., 2018). Importantly, the PA guidelines for Americans emphasize that older adults should determine their level of PA intensity in relation to their level of physical fitness (Piercy et al., 2018). For older adults specifically, multicomponent training, including postural balance exercises with aerobic and strength training three times per week, is recommended as part of the weekly PA routine (Bull et al., 2020; Piercy et al., 2018). The WHO guidelines also include flexibility and walking exercises in multicomponent training for older adults (Bull et al., 2020). Current evidence suggests that some PA is better than no activity at all and that increasing PA even to a level below the recommended amount may bring substantial health benefits. Limiting SB and replacing it with PA of any intensity is therefore now recommended in both large-scale guidelines (Bull et al., 2020; Piercy et al., 2018). The Finnish PA recommendations for older adults are based on a scientific report (Physical Activity Guidelines Advisory Committee, 2018) on the American guidelines and follow the international guidelines in broad outline. However, some differences exist; the Finnish recommendations only state the lower limit of recommended weekly moderate (⩾150 minutes) or vigorous (⩾75 minutes) PA, emphasize the importance of increasing LPA, and recommend muscle strengthening, balance and flexibility-challenging activities at least twice weekly. They also include breaking up sedentary time and restorative sleep (UKK Institute, 2019).

The general PA recommendations also apply to people living with specific chronic conditions, such as hypertension and type II diabetes (Bull et al., 2020;

Dempsey et al., 2020). The PA guidelines for Americans suggest that older adults living with chronic conditions should be aware of if and how their conditions may affect the safety of engaging in PA (Piercy et al., 2018), although recommendations are lacking for people living with more than one chronic condition (Muth et al., 2019). Older adults, who cannot meet the general recommendations due to their chronic conditions, should be as physically active as their abilities and conditions allow (Piercy et al., 2018).

The latest PA recommendations suggest that MVPA of any bout length is beneficial and counts towards the target total volume (Bull et al., 2020; Piercy et al., 2018). This is a major difference from the previous guidelines, which recommended MVPA in bouts of at least ten consecutive minutes (Nelson et al., 2007). In the present study, "the PA recommendations at the time" refers to these older recommendations which were in place when the data collection was planned and initiated.

2.4.2 Physical activity among older adults

PA preferences and activity levels change with aging with declines in both spontaneous and voluntary PA (Nair, 2005). Studies using accelerometers have shown that the amount of PA in general and MVPA in particular decline and that the decline accelerates with advancing age (Arnardottir et al., 2013; Buchman et al., 2014; Hagströmer et al., 2015; Martin et al., 2014). Lower intensity activity types are typically preferred more by older than younger adults (DiPietro, 2001). Walking is the single most important type of PA, other preferred activities being swimming and aquatic fitness, aerobic activities in general, gardening and yard work, dancing, and cycling (Amireault et al., 2019). Among Finnish older adults, the most common activity types are walking and domestic activities, such as household chores and gardening, with less than one in five engaging in muscle strengthening exercise (Wennman & Borodulin, 2021).

The prevalence of physical inactivity, i.e., not meeting the recommended amount of at least 150 minutes of moderate or 75 minutes of vigorous activity per week, or any equivalent combination of these, is high among older adults worldwide. In Europe, approximately every second individual aged 60 years or older is physically inactive (Hallal et al., 2012; Sun et al., 2013). When muscle strengthening activities are included, the proportion of older adults meeting the PA recommendations is even smaller. In the European Union, only 11% of adults aged 65-74 years and 7% of those aged 75 years and older meet the aerobic activity recommendation and perform muscle strengthening activities at least twice per week (Bennie & Wiesner, 2021). It should be noted, that the evidence from large-scale studies is commonly based on self-reported PA and on the older PA guidelines requiring MVPA to be performed in bouts of at least ten consecutive minutes. When PA is measured with accelerometers and all bout lengths are included in the total target volume, the proportion of people meeting the aerobic part of the recommendation increases substantially (Zenko et al., 2019).

In several cross-country studies, Finland has been among those with the highest PA levels (Bennie & Wiesner, 2021; Guthold et al., 2018). However, of the 65- to 74-year-old participants in a large population-based Finnish study, only 27% reported sufficient aerobic activity, 11% muscle strengthening, and 5% postural balance enhancing activities at least twice per week, whereas the corresponding proportions among the participants aged ⩾ 75 years were 12%, 5%, and 4%. Only 7% of those aged 65-74 years and 2% of those aged ⩾75 years met the recommendations for both aerobic activity and muscle strengthening and/or balance enhancing activities (Bennie et al., 2017). In another population-based study, 26% of men and 20% of women aged 65 or older met the recommendations for both aerobic and muscle strengthening activities (Wennman & Borodulin, 2021).

In studies among Finnish older adults, the amount of daily MVPA has varied between approximately 35-50 minutes per day, and LPA between two and three hours per day. The average amount of SB has varied from approximately eight to ten hours in different studies, with lower values reported in studies separating standing from SB (Gao et al., 2020; Husu et al., 2016; Iso-Markku et al., 2018; Kujala et al., 2019). This is comparable to the average of 9.4 hours of SB recorded by older adults in studies utilizing accelerometers (Harvey et al., 2015). In general, the distribution of daily activity in the categories MVPA, LPA, and SB in the Finnish studies is comparable to that reported in studies of older adults in other European countries, although the proportion of MVPA may be slightly higher in Finland (Arnardottir et al., 2013; Giné-Garriga et al., 2020).

Many older adults do not or are unable to maintain MVPA, as standardly defined, in longer bouts (Schrack et al., 2016), as is also seen in the Finnish data. Husu and colleagues (2016) found that their participants averaged less than one bout of 5–15 minutes of consecutive MVPA per day, and approximately two bouts of 15 minutes or more per week. In turn, the participants in the study by Gao and colleagues (2020) averaged less than one continuous activity bout longer than 10 minutes per day, irrespective of the intensity of the activity. Furthermore, older adults rarely engage in high-impact activities, which are considered important for bone health, the numbers of potentially osteogenic high-intensity impacts reported in the few studies investigating impact quantities among older adults being very low (Deere et al., 2016; Hannam, Deere, Hartley, Clark, et al., 2017; Tobias, 2014). Impact-based PA has not previously been studied among Finnish older adults.

2.4.3 Factors affecting physical activity in old age

There is consistent evidence that several individual-level factors such as age, sex, health status, self-efficacy, and previous PA behavior are important determinants of PA in the general population. The social and physical environment may also have a significant impact (Bauman et al., 2012). Less research has focused on the determinants of PA among older adults. A greater number of chronic conditions, multiple medications, higher BMI, and poor physical functioning have been suggested as having an inverse relationship with PA in older age (Giné-Garriga et al., 2020; Koeneman et al., 2011; van Stralen et al., 2009). In turn, higher self-efficacy is one of the predictors most consistently associated with higher PA, including in older age (van Stralen et al., 2009). Important determinants of self-efficacy are executive functions (McAuley, Szabo, et al., 2011), i.e., the set of neural processes that define cognitive control, which in turn is a key factor in PA behavior (Buckley et al., 2014).

Older adults' perceptions of facilitators and barriers to PA have been more extensively investigated. Facilitators include social networks as well as recognized physical and psychological benefits of PA for health and functioning. Typical barriers include physical limitations, environmental barriers, dependence on a professional exercise instructor, and competing priorities. Moreover, the necessity or effectiveness of PA is often not recognized (Franco et al., 2015). In Finnish older adults, poor health, fear and negative experiences have also been identified as common barriers to PA, especially among those who perceive mobility limitations (Rasinaho et al., 2007). The neighborhood environment, in turn, may contain both barriers and facilitators of PA (Portegijs et al., 2020; Rasinaho et al., 2007). A walkable environment near the home and attractive destinations act as facilitators of PA (Portegijs et al., 2017, 2020). In general, destinations such as services, recreational facilities, and open public spaces are strongly related to older adults' PA (Barnett et al., 2017). Therefore, special circumstances, such as the outbreak of the COVID-19 pandemic, which restricted the availability of these destinations, may negatively influence older adults' PA.

2.4.3.1 Multimorbidity

The prevalence of chronic conditions increases with increasing age, and the majority of older adults have at least two such conditions, i.e., have multimorbidity (H. Nguyen et al., 2019; Ofori-Asenso et al., 2019; Salive, 2013). While multimorbidity substantially increases mortality risk, it also affects older adults' daily living via its detrimental impact on physical function, quality of life and psychological well-being (Marengoni et al., 2011). Multimorbidity is interrelated with physical inactivity and deterioration in physical function. Physical inactivity is well-known as one of the main risk factors for chronic conditions and a predictor of multimorbidity (Balogun et al., 2021; Dhalwani et al., 2017; Katzmarzyk et al., 2022; Wagner & Brath, 2012; Wikström et al., 2015). The prevalence of multimorbidity is notably higher in minimally active individuals compared to those who engage in moderate or vigorous activity on a weekly basis (Dhalwani et al., 2016). PA in general and several specific exercise modalities prevent the accumulation of chronic conditions and delay the progression of existing conditions (Pedersen & Saltin, 2015; Piercy et al., 2018). Unfortunately, older adults with one or more chronic conditions tend to be less active than healthier peers (Ashe et al., 2009; Chudasama et al., 2019; Steeves et al., 2019).

Furthermore, multimorbidity associates with poorer physical function and predicts future declines in functioning (Marengoni et al., 2021; Ryan et al., 2015). A greater number of existing chronic conditions and the development of new conditions predicts accelerated functional decline (Lange-Maia et al., 2020; Ryan et al., 2015). Chronic conditions limiting mobility are likely to lead to a further decrease in PA and greater deterioration in physical functioning. Among Finnish older adults, those with mobility-limiting conditions accumulated only half the amount of MVPA and notably less LPA than counterparts who reported no mobility-limiting conditions (Kujala et al., 2019). It has been suggested that in community-dwelling older adults multimorbidity is more common in women than men (Salive, 2013), and that women seem to be more vulnerable than men to the negative impact of multimorbidity on physical function (Calderón-Larrañaga et al., 2019). Multimorbid older women may thus be at greater risk for further decreased PA than multimorbid men.

Chronic conditions in general have been considered in the most recent PA guidelines, and older adults are recommended to be as active as their conditions allow (Bull et al., 2020; Piercy et al., 2018). Although PA guidelines for people living with multimorbidity are currently lacking (Muth et al., 2019), exercise interventions seem to be both beneficial and safe also for them (Bricca et al., 2020). For example, while multimorbidity is associated with increased mortality risk, the risk is attenuated in highly active multimorbid people (Chudasama et al., 2019; Martinez-Gomez et al., 2017). Despite the fact that for people with chronic conditions the benefits of PA outweight the risks, they continue to perceive high risks related to PA (Reid et al., 2021). Poor health and chronic conditions are often cited as barriers to PA among older adults (Franco et al., 2015), despite the further health risks incurred by avoiding PA on these grounds. The role of physical training in the treatment of multimorbidity and the promotion of physical health among multimorbid people have been nominated as research priorities (Parker et al., 2019).

2.4.3.2 Executive functions

Executive functions (EFs) are the higher order cognitive processes required for planned and goal-oriented behavior (Alvarez & Emory 2006). Core facets of EFs include inhibition, such as resisting impulsive behavior and stimuli from the environment, updating and monitoring the working memory, and cognitive flexibility, e.g., flexible task switching and adapting to changed circumstances (Diamond, 2013). Deterioration in EFs is part of the normal aging process due to changes in brain volume and structure, and alterations in some aspects of EFs can already be seen in late middle age (De Luca & Leventer, 2008).

EFs influence PA behavior in many ways. For example, walking is a complex process that makes demands on EFs: one must have the ability to control the movement of the limbs appropriately, be aware of one's destination, and be able to plan a route and navigate possibly challenging circumstances in order to reach the desired destination (Yogev-Seligmann et al., 2008). Better EFs are related to faster walking speed (Demnitz et al., 2016), and greater age-related decline in EFs is associated with greater decline in walking speed (Callisaya et al., 2015). EFs are also suggested to underlie self-regulation (Hofmann et al., 2012). Self-regulatory processes, in turn, are required to change and maintain healthy behaviors, such as the adoption of a physically active lifestyle (Schwarzer, 2001). According to the temporal self-regulation theory, EFs are important for PA behavior since they influence an individual's ability to choose a behavior that is uncomfortable and requires acute exertion but brings long-term benefits instead of choosing a pleasant behavior that may have negative long-term consequences (P. A. Hall & Fong, 2015). A person with higher EFs may therefore choose to walk for errands instead of driving a car. Furthermore, EFs may be important for PA behavior in circumstances where habitual PA routines cannot be followed, since they facilitate adaptation to new and challenging situations (Collette et al., 2006).

Research among older adults indicates that better EFs are related to a higher level of PA, better adherence to an exercise intervention, and maintenance of PA following a structured physical training program (Best et al., 2014; Daly et al., 2014; Davis et al., 2021; McAuley, Mullen, et al., 2011), although the evidence is not consistent across all aspects of EFs (Davis et al., 2021). The relationship between EFs and PA is, moreover, bidirectional (Daly et al., 2014). There is consistent evidence that physical training can improve all the domains of EFs in older adults (F.-T. Chen et al., 2020; Xiong et al., 2021). EFs can also be improved with cognitive training (L. Nguyen et al., 2019). A recent meta-analysis, in turn, suggested that combined physical and cognitive training may be the most effective training regimen to improve EFs in older adults (Malmberg Gavelin et al., 2021). However, it is not known if targeted training in EFs may facilitate PA in older adults.

2.4.3.3 COVID-19

The COVID-19 pandemic, which broke out early in 2020, has raised concerns about further reduction in population PA levels (G. Hall et al., 2021). Mobility was restricted across the world with measures such as lockdowns, mass quarantines, and stay-at-home recommendations aimed at mitigating the spread of the virus (Kraemer et al., 2020). One of the most apparent detrimental effects of these restrictions on movement was decreased PA (Lippi et al., 2020). In Finland, several COVID-19-related restrictions came into force in spring 2020, including the closure of public sports facilities, suspension of group activities, and recommendations to avoid physical contact with others, all of which limited opportunities for PA and exercise. Furthermore, older adults were advised to self-quarantine during the first months of the pandemic, constraining their PA opportunities even more than those of the general population.

Changes in PA from before to during COVID-19 have been widely investigated with self-reports (Christensen et al., 2022; Stockwell et al., 2021). A systematic review covering almost 90 000 participants showed consistent evidence for decreased PA in healthy adults from pre-COVID-19 to during lockdown measures but did not distinguish between working-age and older adults (Stockwell et al., 2021). Only a few studies have investigated changes by age group (Christensen et al., 2022). The few studies conducted among or reporting separately on older adults have shown mixed results. Several studies have shown a decrease in PA from pre- to during COVID-19 in older age groups (Bourdas & Zacharakis, 2020; Mazo et al., 2021; Yamada et al., 2020). In contrast, a large population-based British study showed that older adults reported more weekly activity during the COVID-19 restrictions than before the pandemic (Strain et al., 2022). A general limitation of these studies is their cross-sectional and retrospective nature. One longitudinal study conducted among Finnish older adults found higher PA during the early months of the pandemic compared to two years earlier (Leppä et al., 2021). Another study based on the same data reported that participants regularly visited a similar number of physical exercise destinations during the pandemic as two years earlier, with the difference that the exercise destinations they visited during the pandemic were closer to their homes (Portegijs et al., 2021), indicating that they maintained their habitual PA level but changed their PA types or settings during the recommendations to restrict their movement.

2.5 Physical and cognitive training interventions to promote physical activity in old age

A wide range of interventions have been successful in promoting PA among older adults (Taylor et al., 2021). Two main types of intervention strategies, behavioral and cognitive, may be effective. The components of behavioral interventions engage participants to actively change their PA behavior. Such strategies improve participants' abilities and opportunities to be physically active. Cognitive components, in turn, facilitate change in cognitive processes, attitudes, or beliefs and may therefore improve motivation to be physically active (Chase, 2015; Grande et al., 2020; Zubala et al., 2017). Since the pathways to increased PA may differ between the two types of interventions, it has been suggested that interventions that include both behavioral and cognitive components would be more effective in increasing PA among older adults than either type alone (Chase, 2015; Lachman et al., 2018).

Of the behavioral type interventions, structured physical training programs are known to increase older adults' PA (Sansano-Nadal et al., 2019). Physical training interventions typically include skills training, the provision of exercise equipment, and teaching exercise routines (Lachman et al., 2018), however, the design of the intervention may markedly influence its impact on PA. Training at moderate intensity and self-monitoring of PA behavior have both been recognized as effective strategies. Furthermore, exercising in groups, center-based training sessions, and intensive contacts with instructors have proven successful as intervention strategies among older adults (Conn et al., 2002). Such long-term exercise programs may be effective because they offer social connectedness and allow participants to experience empowerment and the energizing effects of being part of a group (Farrance et al., 2016). Physical training interventions may also facilitate both an increase in and maintenance of PA through other pathways. It is widely recognized that physical training improves cognitive functioning, especially EFs, in older age (Erickson et al., 2019). EFs in turn may moderate the link between the intention to be physically active and actual PA behavior (P. A. Hall et al., 2008). Furthermore, participation in physical training increases self-efficacy for being physically active and engaging in exercise, thereby facilitating increases in PA (McAuley, Mullen, et al., 2011). For example, the results of the LIFE study – the largest randomized controlled trial (RCT) testing the effects of physical training among older adults implemented thus far – showed that progressive multicomponent physical training markedly reduced sedentary time and increased PA (Fielding et al., 2017). The training program combined twice-weekly center-based exercising in groups and home-based PA goals. Physical training targeted both aerobic endurance, muscle strength, balance, and flexibility, and was supported with cognitive approaches aimed at, e.g., increasing self-efficacy (Fielding et al., 2011).

Targeted cognitive training is a specific cognitive intervention approach that can be performed, for example, by means of computer programs. It is known that cognitive training is more effective in improving EFs than physical training, and it is also suggested to increase cognitive control. Improved EFs and cognitive control may, in turn, facilitate engagement in PA during the intervention and better maintenance of a physically active lifestyle thereafter (Best et al., 2014; Buckley et al., 2014; McAuley, Mullen, et al., 2011; Meng et al., 2022; L. Nguyen et al., 2019). This theoretical approach is supported by preliminary evidence from a large three-year RCT showing that a multidomain intervention including cognitive training and PA counseling with nutritional components led to increased PA among older adults (de Souto Barreto et al., 2018). However, the cognitive training intervention effects were not compared to PA counseling alone. Another possible pathway from cognitive training to increased PA is that cognitive training may improve some aspects of physical capacity, especially walking ability in challenging conditions, make more demands on EFs (Marusic et al., 2018). However, this is not supported by all studies (Verghese et al., 2021), and hence the transfer effects of cognitive training on everyday life require more research (Buckley et al., 2014).

Interest in combining physical and cognitive training has grown during recent years; however, the research focus has mainly been on cognitive outcomes (Lachman et al., 2018). In general, combined training and cognitive training interventions are more effective on cognitive functioning than physical training alone, whereas combined training and physical training are more effective on physical functioning than cognitive training alone (Malmberg Gavelin et al., 2021). Improved cognitive and physical function can both independently facilitate PA behavior. In a large Finnish RCT study, a multidomain lifestyle intervention involving cognitive and physical training with educational components led to increased PA among older adults (Ngandu et al., 2015). Thus far, however, no research exists on the additive effects of combined physical and cognitive training on PA above physical training alone. In general, the positive effects of physical training interventions on PA tend to be short-lived and attenuate over time. New strategies are therefore needed to improve PA through long-term interventions and to support the maintenance of a physically active lifestyle following a structured physical training intervention (Sansano-Nadal et al., 2019). In sum, complementing physical training with cognitive training may be a potential intervention strategy to increase and support the maintenance of PA among older adults.

3 PURPOSE OF THE STUDY

The purpose of this doctoral dissertation was to investigate the level of physical activity and its association with body composition and physical capacity in community-dwelling older adults. A further aim was to investigate changes in physical activity during a 12-month multicomponent intervention, at a one-year follow-up, and during the COVID-19 restrictions among community-dwelling older adults who did not meet the current physical activity recommendations prior to the intervention. The specific aims of the study were:

1. To describe, utilizing questionnaire- and accelerometer-based methods, the physical activity levels among community-dwelling older adults and to investigate the mutual associations of the physical activity outcomes. (Sub-studies I–III, unpublished data)

2. To investigate the associations of accelerometer-based physical activity in intensity categories and across the intensity range with body fat, lean mass, and physical capacity among older adults. (Sub-study I)

3. To investigate the associations of accelerometer-based physical activity intensities, impact intensities and an osteogenic index with proximal femur bone traits among older adults. (Sub-study II)

4. To investigate the impact of multimorbidity patterns on physical activity and physical capacity among older adults during a 12-month physical and cognitive training intervention, and on physical activity at a one-year follow-up. (Sub-study III)

5. To investigate the effects of 12-months of physical and cognitive training compared to physical training alone on physical activity during the intervention, at a one-year follow-up, and during the COVID-19 restrictions among older adults. (Sub-study IV, unpublished data)

6. To investigate whether executive functions predicted changes in physical activity during the 12-month physical and cognitive training intervention, at one-year follow-up, and during the COVID-19 restrictions among older adults. (Sub-study IV)

4 MATERIALS AND METHODS

4.1 Study design and participants

This study utilized data from a larger research project, Promoting safe walking among older people (the PASSWORD study), conducted at the Gerontology Research Center, Faculty of Sport and Health Sciences, University of Jyväskylä, during the years 2017–2020 (Sipilä et al., 2018, 2021). The PASSWORD study was a 12-month assessor-blinded RCT (ISRCTN52388040) with a one-year follow-up. An extended follow-up was conducted during the outbreak of COVID-19 in Finland. The study flow is shown in Figure 1. The main aim of the PASSWORD study was to investigate the effects of physical and cognitive training on older adults' walking speed, falls and EFs compared to physical training only. The target sample size, based on a priori power calculations for the main outcome, 10-meter maximal walking speed, was 310, i.e., 155 in each study group (Sipilä et al., 2018, 2021). Participants were recruited between February 2017 and March 2018 from a random sample (n = 3 862) drawn from the Finnish national population registry. An information letter about the study was first mailed to potential participants, after which they were contacted by telephone to assess their eligibility and willingness to participate. The inclusion criteria for the PASSWORD study were age 70-85 years, community-living in Jyväskylä, physically inactive (less than 2.5 hours per week of moderate intensity activity in bouts of at least ten minutes and no regular resistance training), able to walk 500 meters without assistance from another person, a Mini-Mental State Examination (MMSE) test score of 24 or higher, and willingness to provide an informed consent. Exclusion criteria included severe chronic conditions and/or medication affecting physical and/or cognitive functioning, diseases and other factors that could interfere with participation in the study or with exercise safety, severe vision or hearing impairment, excessive alcohol consumption, and another member of the same household participating in the study (Sipilä et al., 2018).

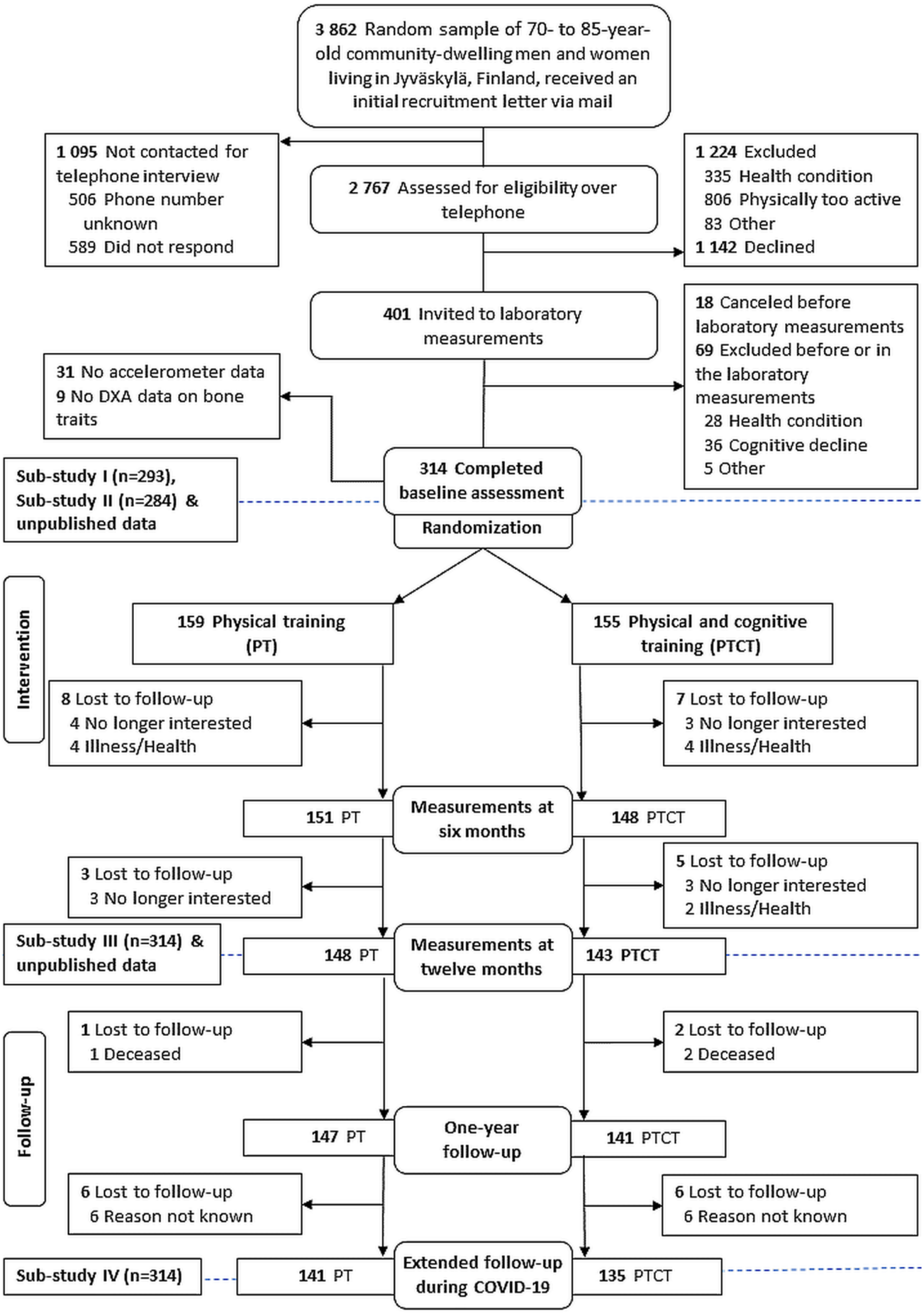

FIGURE 1 Flow chart of the study. Dashed horizontal lines refer to the parts of the PASSWORD study included in each sub-study.

Older adults, who met the inclusion criteria, did not report any exclusion criteria, and were willing to participate, were invited to the laboratory measurements. Clinical inclusion and exclusion criteria were assessed by the study nurse and, if necessary, study physician and clinical psychologist before the baseline measurements. Of the 401 older adults invited to the laboratory assessments, 314 completed the baseline measurements and were recruited. The comprehensive assessments included a health status examination, questionnaires, physical and cognitive tests. After the baseline measurements, participants were randomized into a physical and cognitive training (PTCT, n=155) or physical training (PT, n=159) group. Participants were randomized into the study groups in a 1:1 ratio in randomly varying blocks of two and four, stratified by sex and age group (70-74, 75-79, and 80-85 years) utilizing a computer-generated random allocation sequence. Randomization was performed by a researcher who did not participate in the data collection. Measurements were repeated after six and twelve months (Sub-study III, data on study groups combined, and unpublished data). At the one-year follow-up, participants received a questionnaire via mail with a prepaid envelope. A second follow-up questionnaire was mailed to the participants in April 2020, during the COVID-19 restrictions. The interval between responding to the one-year follow-up and the COVID-19 questionnaires varied between two weeks and sixteen months, depending on the recruitment date. Of the initially recruited 314 participants, 288 and 276 returned the one-year and COVID-19 follow-up questionnaires, respectively (Sub-study IV). The timeline of the study is presented in Figure 2.

4.2 Ethics

The PASSWORD study and its extended follow-up during the COVID-19 restrictions were approved by the Ethics Committee of the Central Finland Health Care District (14/12/2016, ref: 11/2016; 24/4/2020, ref: 11U/2016), and the study conformed with the principles set out in the Declaration of Helsinki. All participants signed a written informed consent before attending any measurements. Participation was voluntary and participants had the right to withdraw at any time during the study without providing a reason. The research assistants who participated in the data collection and supervised the interventions were trained to ensure the safety and protection of privacy of the participants. The physical training sessions were supervised by students of physiotherapy and master's degree students in sport and health sciences. The cognitive training sessions were supervised by master's degree students with psychology as at least a minor subject. The research assistants received training in first aid and, if necessary, were ready to give first aid during the laboratory visits and training sessions. Potential adverse events were screened throughout the study. Participants reported new symptoms and injuries every three months via a health status questionnaire and, if needed, could visit the study nurse and/or physician.

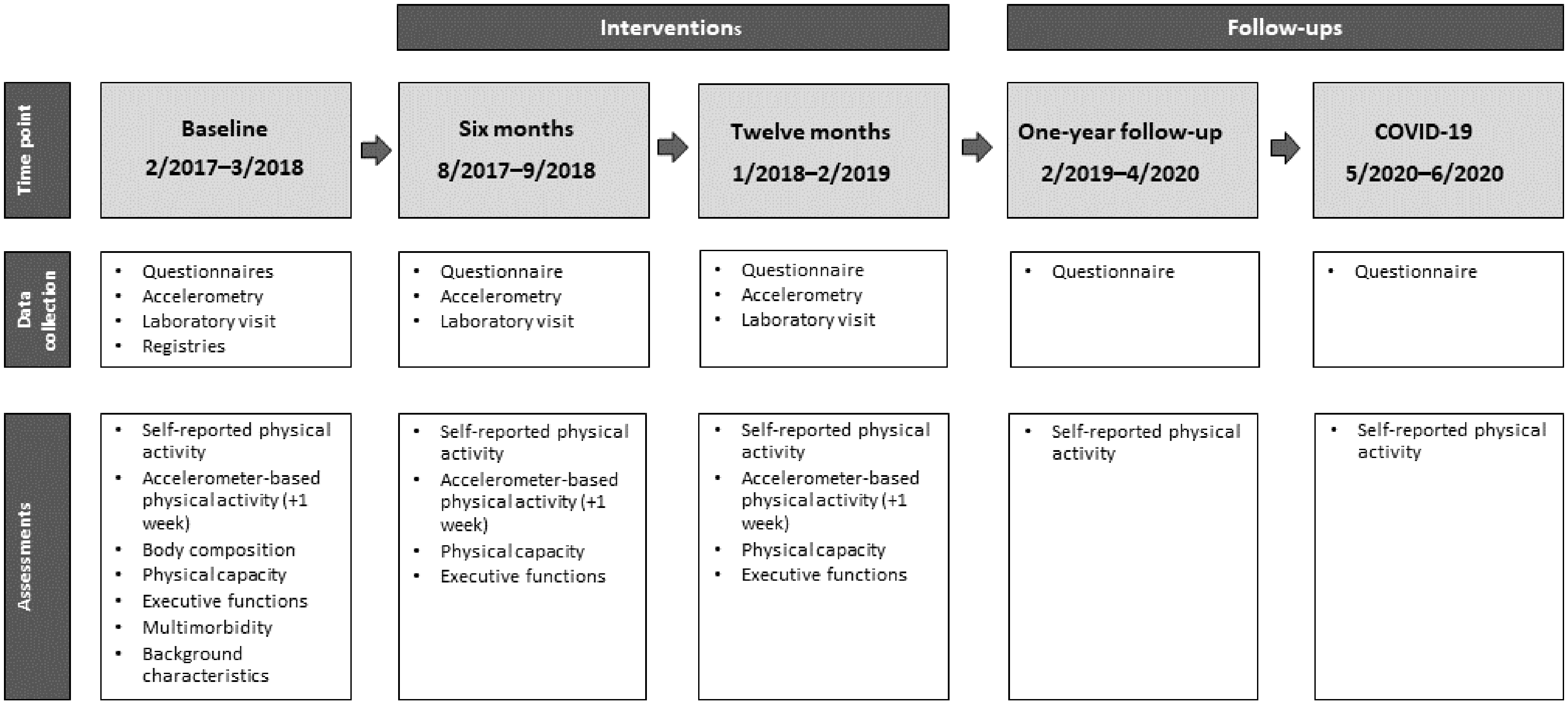

FIGURE 2 Timeline of the study.

4.3 Measurements

The measurements used in this study are summarized in Table 1 and only briefly presented in this section. The variables and measurements are described in more detail in the original publications.

4.3.1 Physical activity

4.3.1.1 Self-reported physical activity

Self-reported current PA category (SRPA) was assessed with a one-item questionnaire with seven response options (Sub-studies III & IV) and is a modification of the widely-used single-item questionnaire with four response options originally developed by Saltin and Grimby in the 1960s (Saltin & Grimby, 1968). The Finnish version was first presented by Hirvensalo and colleagues (1998) as a six-scale instrument. The revised seven-scale instrument applied in the present study has previously been used in other Finnish studies (Hyvärinen et al., 2019; Kovanen et al., 2018). The response options to the question "Which of the following descriptions best corresponds to your physical activity at the moment?" were: 0) I do not move more than is necessary in my daily chores, 1) I go for casual walks and engage in light outdoor recreation 1–2 times a week, 2) I go for casual walks and engage in light outdoor recreation several times a week, 3) I engage 1–2 times a week in brisk physical activity (e.g., yard work, walking, cycling) to the point of perspiring and some degree of breathlessness, 4) I engage several times a week in brisk physical activity (e.g., yard work, walking, cycling) to the point of perspiring and some degree of breathlessness, 5) I do keep-fit exercises several times a week in a way that causes rather strong shortness of breath and sweating during the activity, 6) I participate in competitive sports and maintain my fitness through regular training. In Sub-study IV the three highest categories (4-6) were combined for the analyses. Participants completed the questionnaires at home before each laboratory visit, approximately one year after the last laboratory visit, and during the COVID-19 restrictions.

4.3.1.2 Accelerometer-based physical activity

Accelerometer-based PA and impact intensity and volume were measured with a hip-worn tri-axial accelerometer (UKK RM42, UKK Terveyspalvelut, Tampere, Finland). At the end of each laboratory visit, participants received both oral and written information on how to wear the accelerometer for seven consecutive days during waking hours, except during water-related activities, beginning from the following morning. The baseline accelerometer-assessment was completed before the physical training intervention began, the six-month assessment was conducted in the middle of the intervention during the physical training, and the twelve-month assessment was conducted at the end of the intervention, i.e., after the structured physical training. Participants wore the accelerometer during their waking hours, except during water-related activities, on the right hip, and kept a diary during their wear days. The accelerometers were returned by mail in a prepaid envelope or to the study personnel when the participant visited the laboratory for an initial information session or the first training session.

The raw acceleration data were analyzed with in-house developed MATLAB (version R2016b, The MathWorks Inc., Natick MA, USA) scripts. For all the analytical approaches, the magnitude of the resultant acceleration (Euclidian norm, $\sqrt{x^2+y^2+z^2}$) of the three axes was calculated. The accelerometer use dates were controlled from the diaries, and the resultant magnitude data were thereafter considered in 24-hour epochs from midnight to midnight. To investigate physical activity intensity, the resultant magnitude was summarized in non-overlapping five-second epochs using mean amplitude deviation (MAD; Sub-studies I & II). To calculate the MADs, the mean of each five-second epoch was calculated and subtracted from the magnitude of the resultant accelerations, negative values were changed to positive, and the mean of these absolute values was used as the MAD for the given epoch. Thereafter, mean MAD of each one-minute epoch was calculated from the five-second epoch means. The mean daily minutes of PA were then divided into sedentary (< 0.0167 g), light (0.0167 to < 0.091 g), moderate (0.091 g to < 0.414 g), and vigorous (⩾ 0.414 g) activity, utilizing previously validated cut-offs (Vähä-Ypyä, Vasankari, Husu, Mänttäri, et al., 2015; Vähä-Ypyä, Vasankari, Husu, Suni, et al., 2015; Sub-studies I & II, unpublished data). Due to the almost non-existing amount of vigorous PA, the categories of moderate and vigorous PA were combined for further analyses into MVPA. To facilitate a more detailed inspection of the PA intensity distribution, the intensity range from zero to 1.2 g was divided into logarithmically equidistant bins (Belavý et al., 2017; Sub-study I). This approach resulted in 93 bins with at least some recorded activity, the bins being narrower at the lower and wider at the higher intensities. Mean daily activity minutes in each bin were calculated.

Potential osteogenic impacts were investigated utilizing two different accelerometer-data processing approaches to identify peak accelerations (Sub-study II). First, each sample of the resultant magnitude that was higher than that of both the preceding sample and subsequent sample were identified as an acceleration peak. The magnitude of each peak was noted, and the peaks were classified as low (> 1.5 g to 2.0 g), medium (> 2.0 g to 2.5 g), or high (> 2.5g) (Deere et al., 2016). The number of peaks in each category was then summarized for each 24 hours. Second, an osteogenic index, which is a summary score of the magnitude and volume of the impact peaks, was calculated (Ahola et al., 2010 Belavý et al., 2019). Continuous acceleration peaks exceeding 1.3 g were identified and the maximum value of each peak was noted. The peaks were then assigned to 32 intensity bins from 1.3 g to 10.3 g, with all peaks exceeding 10.3 g assigned to a final bin. The logarithm of the number of peaks in each bin was then multiplied by the lower cut-off of the given bin, and the values were summed and used as the daily osteogenic index score.

TABLE 1 Measurements and references used in the sub-studies.

Measurement	Sub-study	Devices and references
Physical activity		
Self-reported current physical activity category	III, IV	(Hirvensalo et al., 1998)
Accelerometer-based physical activity	I–II	Tri-axial accelerometer (UKK RM42, UKK Terveyspalvelut, Tampere, Finland)
Accelerometer wear-time, h/d	I–II	(Belavý et al., 2017)
Valid accelerometer days, no.	I–II	
Sedentary, light, and moderate-to- vigorous intensity physical activity, min/d	I–II	(Vähä-Ypyä, Vasankari, Husu, Mänttäri, et al., 2015; Vähä-Ypyä, Vasankari, Husu, Suni, et al., 2015)
Physical activity in detailed intensity ranges, min/d	I	(Belavý et al., 2017)
Low, medium, and high impacts, no./d	II	(Deere et al., 2016)
Impacts in detailed intensity ranges, no./d	II	(Ahola et al., 2010; Belavý et al., 2019)
Osteogenic index, mean score	II	(Ahola et al., 2010; Belavý et al., 2019)
Physical capacity		
Lower extremity functioning, Short Physical Performance Battery	I, II, IV	(Guralnik et al., 1994)
Aerobic endurance, 6-min walking distance, m	I, III	20-m indoor track (ATS Committee on Proficiency Standards for Clinical Pulmonary Function Laboratories, 2002)
Maximal walking speed over 10-m, m/s	I	Indoor track, photocells (Sipilä et al., 1996)
Maximal knee-extension strength, kg	III	Dynamometer chair (Good Strength Metitur Ltd, Palokka, Finland) (Sipilä et al., 1996)
Muscle power, five-time chair stand time, s	III	Stopwatch (Guralnik et al., 1994)
Anthropometry and body composition		
Body height, m	I–IV	Stadiometer
Body weight, kg	I–IV	Digital scale
Body mass index, kg/m^2	I–IV	
Waist circumference, cm	I, III	Tape measure
Fat percent	I, III	DXA[a]
Appendicular lean mass, kg	I, III, IV	DXA[a]

Measurement	Sub-study	Devices and references
Femoral neck and total femur bone mineral content, g	II	DXA[a]
Femoral neck and total femur bone mineral density, g/cm^2	II	DXA[a]
Femoral neck section modulus, mm^3	II	DXA[a]
Femoral neck minimal width, mm	II	DXA[a]
Femoral neck T-Score	II	DXA[a]
Cognitive functioning		
Global cognition; Mini-Mental State Examination	III	(Folstein et al., 1975)
Inhibition; Color-word Stroop	IV	(Graf et al., 1995)
Set shifting; Trail Making Test B–A	IV	(Reitan, 1958)
Working memory; Letter verbal fluency	IV	(Koivisto et al., 1992)

[a]DXA = Dual-energy x-ray absorptiometry, with LUNAR Prodigy (GE Healthcare, Madison, WI, USA) and analysis software Lunar Prodigy Advance Encore v. 14.10.022.

Accelerometer wear-time was defined by removing any epoch of at least 60 minutes in which the one-minute MAD values were continuously below 0.02 g (Belavý et al., 2017). Participants with valid data, i.e., $\geqslant$ 3 days of $\geqslant$ 10 hours of wear time, were included in the analyses. For each participant, mean values for all accelerometer-based PA outcomes were calculated for the days with at least 10 hours of wear time and subsequently used in all the PA intensity and impact-based analysis approaches.

4.3.2 Anthropometry and body composition

Body height as meters (m) was measured with a stadiometer, weight as kilograms (kg) with a digital scale, and waist circumference in centimeters (cm) with a tape measure by the study nurse during the health examination. BMI was calculated as kg/m^2. Participants underwent a whole-body dual-energy x-ray absorptiometry (DXA, LUNAR Prodigy, GE Healthcare, Madison, WI, USA) scan for body fat and lean mass and a dual-femur scan for bone properties of the femurs. Total fat mass (kg), fat percent and appendicular lean mass (ALM, kg) were derived from the whole-body scan utilizing the Lunar Prodigy Advance Encore v. 14.10.022 analysis software. Dual-femur scans were analyzed for total femur and femoral neck bone mineral content (BMC, g) and density (BMD, g/cm^2), and for the femoral neck T-score. Advanced hip structural analysis was used to calculate section modulus (SM, mm^3), which is an index of bending strength, and minimal neck width (MNW, mm), which is the narrowest outer diameter of the femoral neck. The mean values of both femurs were calculated and used as the outcome values. For participants with a hip replacement on one side, the values of the non-operated side were used as the outcome values.

4.3.3 Physical functioning and physical capacity

Overall physical functioning was assessed with a single-item four-scale question. Participants were asked to rate their current mobility with response options ranging from very good to very poor. Difficulties in outdoor mobility were assessed with the question “Are you able to move outdoors?”, with five response options ranging from “Yes, without problems” to “Not even with assistance from another person”. The laboratory-based physical capacity assessment comprised measurements of lower extremity functioning, endurance, walking speed, and muscle strength. Overall lower extremity functioning was assessed with the Short Physical Performance Battery (SPPB), which consists of three tests: standing balance, habitual walking speed over four meters and five-time chair stand time. A summary score ranging from 0 to 12 is calculated, with a higher score indicating better performance (Guralnik et al., 1994). Chair-stand test time was also used independently as a measure of lower extremity muscle power. Six-minute walking distance (6-min walk) was used to assess aerobic endurance (ATS Committee, 2002). Maximal walking speed over ten meters (10-m walk) was measured using photocells (Sipilä et al., 1996). Maximal isometric knee-extension strength was measured using an adjustable dynamometer chair (Good Strength, Metitur Ltd., Palokka, Finland) on the dominant hand side. The knee angle was set at 60 degrees from full extension with the ankle attached to a strain-gauge. Knee-extension was performed three times or until no further improvement occurred, and the best performance was recorded as the outcome (Sipilä et al., 1996).

4.3.4 Cognitive functioning

Global cognition was assessed with Mini-Mental State Examination (MMSE) test battery (Folstein et al., 1975; Sub-study III). Three tests were used to assess the different aspects of EFs (Sub-study IV). The Stroop color-word test was used as a measure of automatic response inhibition (Graf et al., 1995). The Trail Making Test (TMT) B–A was used to assess cognitive flexibility and set-shifting (Reitan et al., 1958). The Finnish version of Letter Verbal Fluency was used to assess working memory and updating (Koivisto et al., 1992).

4.3.5 Health status

Participants' health status was self-reported in a questionnaire and verified by the study nurse and, if necessary, study physician in a clinical examination. Participants reported their current self-rated health, perceived long-term pain hindering PA in five body sites, chronic conditions, and medication in a questionnaire. Chronic conditions and prescribed medications were verified from the integrated patient register (Effica database) by the study physician. In Sub-study II, oral glucocorticoids, bisphosphonates, and all non-vaginal hormone replacement therapy preparations containing estrogen were recorded. In Sub-study III, chronic conditions were classified into 17 categories based on the International Classification of Diseases codes (Fortin et al., 2017). A deviation from the categorization was made for obesity, which was not dichotomized but used as a continuous variable based on BMI.

4.3.6 Socio-demographic characteristics

Participants' sex and date of birth were drawn from the National Population Register and age on the baseline measurement day was calculated as years. Highest education (categorized as high vs. medium vs. low in Sub-studies I & III or university/college degree vs. no university/college degree in Sub-study IV), smoking status (never vs. former vs. current) and marital status (married/living with a partner vs. not living with a partner) were self-reported in a questionnaire.

4.4 Intervention

4.4.1 Physical training

The multicomponent, progressive physical training intervention for both study groups included supervised and self-administered exercise. The training protocol was adapted from those used in previous studies (Fielding et al., 2011; Portegijs et al., 2008) and the then current PA recommendations for adults aged ⩾65 years (Nelson et al., 2007). Two supervised training sessions in groups of 10–15 participants were organized weekly: one for strength and postural balance training and the other for walking and dynamic balance training. Five to six training periods with varying specificity, intensity, and volume were organized during the intervention year (Sipilä et al., 2018).

The supervised strength training sessions were carried out at three senior gyms in the city of Jyväskylä, all of which were equipped with identical resistance training machines utilizing air-pressure technology (https://www.hur.fi/en/science/technology). Eight to nine exercises targeting the lower body, trunk, and upper body, with an emphasis on the lower limbs, were performed after a warm-up that also included balance exercises. Training was structured to increase muscle strength and power. Individualized training loads were defined based on 6-repetition maximum strength tests, which were administered three times during the study. Training loads were increased during the training periods when the target number of repetitions was achieved.

Supervised walking and dynamic balance sessions were organized in groups of 10–15 participants. Training took place outdoors on a 400-m circular walking path, except during the winter months when it took place in a sports hall with a 200-m oval track. Sessions started with a warm-up at habitual walking speed and dynamic balance exercises, followed by a continuous walk of 10–20 minutes at a self-selected pace with a somewhat hard to hard intensity, i.e., a perceived exertion rating of 13–15 (Borg, 1982). The strength training and walking sessions were supervised by physiotherapy students and master's degree students in sports and health sciences. The supervised exercise sessions lasted from 45 to 60 minutes.

Home-based exercise included a progressive strength, balance, and flexibility training program with a target training frequency of 2–3 times per week and moderate-intensity aerobic activity. Resistance in the strengthening exercises was increased with elastic resistance bands of three resistance levels. In the standing balance tasks, hand, foot, and vision support was diminished over time to increase task difficulty. Stretching of the main muscle groups was included in the home-exercise program. The home-exercise sessions lasted for about 30 minutes each, if performed as instructed. Furthermore, participants were encouraged to accumulate at least 150 minutes per week of outdoor moderate intensity activity in bouts of at least ten minutes. Recommended activity types included walking, Nordic walking, cycling, and cross-country skiing.

Adherence to the supervised training was tracked with training logs kept by the supervisors and, for strength training, logs from the resistance training machines. Adherence to self-administered exercise was tracked from monthly diaries kept by the participants during the intervention period. Adverse events were tracked with health status surveys every three months. Participants had the possibility to consult the study nurse and physician if necessary.

4.4.2 Cognitive training

To allow the participants to adapt to the physical training, the cognitive training component started two months later. The cognitive training was performed on an in-house developed computer program (iPASS), which was a modified version of the cognitive training program utilized in a previous large-scale study (Ngandu et al., 2015). The program targeted the three main facets of EFs, i.e., response inhibition, cognitive flexibility and working memory, and was built on the unity/diversity model of EFs (Miyake et al., 2000). Two task sets, including set-shifting, automatic response inhibition, and working memory updating and maintenance tasks, alternated between the training sessions. Participants were instructed to perform all tasks as quickly and as accurately as possible. Task difficulty increased automatically over the intervention period, as the participants' skills increased. The cognitive training sessions lasted for about 20 minutes at a time, and the target training frequency was 3-4 times per week.

The cognitive training started with supervised group sessions held in a computer class at the University of Jyväskylä. The supervisors were master's degree students with psychology as a minor or major subject. Participants were allowed to start training at home after two to three sessions, but supervised sessions at the University were provided at least once a week. Participants without a computer at home also had the possibility to train in various locations (e.g., libraries) provided by the City of Jyväskylä. Peer support for computer skills was available during the training sessions. Adherence to the cognitive training was tracked from the iPASS-program log-ins.

4.5 Statistical analyses

Statistical analyses were performed mainly with IBM SPSS Statistics, versions 24 and 26 (SPSS Inc., Armonk, NY). Partial correlation analyses investigating the associations of PA and impacts across the intensity range with body composition and physical capacity outcomes were conducted in R programming environment version 3.4.3 (R Core Team, 2017) in Sub-study I and RStudio version 1.2.1335 (RStudio Inc., Boston, MA) in Sub-study II. Multinomial logistic longitudinal path models (MLLPMs) and change score models were constructed with Mplus, version 7.4 (Muthén & Muthén, 1998-2015; Sub-study IV). Generalized estimating equation (GEE) models and Wald tests in Sub-study III were performed in R programming environment version 4.1.1 (R Core Team, 2021). Significance level was set at $p < 0.05$, two-tailed, in all analyses.

4.5.1 Descriptive analyses

Participant characteristics were summarized as means and standard deviations (SD) for continuous variables and as frequencies (n) and percentages (%) for the categorical variables reported in Sub-studies I–IV. The Kolmogorov-Smirnoff test was used to assess the normality of distributions in Sub-study II, and medians and inter-quartile ranges (IQR) were presented for non-normally distributed continuous variables. In Sub-study IV, differences between participants who remained in the study and those who had dropped out at the one-year and COVID-19 follow-ups were compared with independent samples t-test for continuous variables and Pearson's Chi-squared test and Fisher's exact test for categorical variables.

Logarithmic values were calculated for mean daily minutes of PA (Sub-study I) and number of impacts in intensity bins (Sub-study II). PA minutes and impact counts in more detailed intensity ranges were illustrated with histograms showing the numbers of participants who recorded any activity, mean daily minutes of PA, and mean daily impact counts in each intensity bin.

4.5.2 Cross-sectional associations

Multiple linear regression

Cross-sectional associations between PA and proximal femur bone traits were assessed with multiple linear regression models (Sub-study II). Each bone trait was used as a dependent variable in a separate model. Models were built for one PA variable – mean daily minutes in SB, LPA, and MVPA, number of low, medium, and high impacts, and osteogenic index – at a time and adjusted for age, sex, height, weight, SPPB score, smoking, and medication (hormone replacement therapy, oral glucocorticoids, and bisphosphonates). These covariates were chosen as they are generally known to be associated with physical activity and/or bone health. In second phase, two models adjusted for the other intensity bands were built: one including SB, LPA and MVPA and the above-mentioned covariates, and the other including low, medium, and high impacts and the covariates. Sensitivity analyses, in which all participants using the above-mentioned medications were excluded, were performed for similar models.

Correlations

Cross-sectional associations between mean daily minutes of SB, LPA, and MVPA, the number of low, medium, and high impacts, and the osteogenic index were assessed with Pearson's correlation coefficient r (Sub-study II). Associations between self-reported PA category and the accelerometer-based PA outcomes were assessed with Spearman's rho (unpublished data). In Sub-study I, associations of SB, LPA and MVPA with fat percent, ALM, 6-min walk, 10-m walk, and SPPB score were assessed with Pearson's partial correlation coefficient r and adjusted for sex and age in Model 1. In Model 2, the associations between LPA and each of the body composition and physical capacity variables were adjusted for sex, age and MVPA, and the associations of MVPA with body composition and physical capacity with sex, age, and LPA. Sex and age were included as covariates in all models as preliminary analyses indicated differences in physical activity levels by sex and age.

The strength of the relationship between mean daily minutes of activity in each of the logarithmically equidistant intensity bins and each of the body composition and physical capacity variables was calculated as partial correlation coefficient r and 95% confidence interval (CI). The correlation coefficients with 95% CIs were presented as graphs. The graphs were restricted to show associations for physical activity intensities from 0.0188 g to 0.31 g, since the first bin also included non-wear time and less than one third of the participants recorded any activity exceeding 0.31 g. Similar graphs were created for Sub-study II, in which the correlation coefficients and 95% CIs were calculated between each bone trait and the log-transformed number of impacts in each of the 32 impact intensity bins, which were used to calculate osteogenic index. The associations were adjusted for covariates, which had a p-value of < 0.1 in some of the above-mentioned multiple linear regression models for the bone trait in question.

4.5.3 Intervention effects

Generalized estimating equation

The GEE method was used to compare the effects of physical and cognitive training and physical training alone on accelerometer-based PA outcomes (unpublished data) and to investigate the effects of multimorbidity patterns on SRPA and physical capacity outcomes (Sub-study III). The GEE method is an extension of general linear models that can be used with longitudinal data. The method takes into consideration correlations of repeated measures within subjects but assumes that subjects are independent of each other (Liang & Zeger, 1986). The method benefits from not requiring the outcome variable to follow a specific, e.g., normal, distribution. It can also take into account all available data, and thus excluding participants with missing data in a longitudinal study is not necessary (Y. Ma et al., 2012). The intention-to-treat principle was followed in all analyses, i.e., all the participants initially recruited to the study were analyzed as members of the study group into which they had been randomized.

The effects of physical and cognitive training on SRPA and accelerometer-based SB, LPA, and MVPA at six and twelve months were investigated with linear GEE models using the unstructured working correlation and maximum likelihood method (unpublished data). Separate models were conducted for each PA variable as a dependent variable. The main effects of study group and time and the interaction effect of group and time were included as independent variables in the models.

The effects of multimorbidity patterns on the development of SRPA and physical capacity were assessed with GEE linear models with an unstructured working correlation and maximum quasi-likelihood (Sub-study III). Changes in SRPA were tracked from baseline to the one-year follow-up, whereas the changes in physical capacity outcomes were investigated from baseline to twelve months. Separate models were conducted for SRPA and each physical capacity outcome as a dependent variable. Preliminary analyses indicated sex-specific differences in interaction effects, and thus the final analyses were stratified by sex. Models included the main effects of time, BMI, and chronic conditions and their interactions with time as predictors. The main effect of age was included as a covariate, since previous research has shown that higher age is associated not only with lower PA and physical capacity but also a higher number of chronic conditions. The multiparameter Wald test was used to assess the combined effect arising from the cluster of chronic conditions and from BMI + chronic conditions as a combined predictor cluster and from the interaction effects of time x BMI, time x chronic conditions, and time x BMI + chronic conditions.

Multinomial logistic longitudinal path models

MLLPMs were used in Sub-study IV to compare the effects of physical cognitive training and physical training alone on repeated measurements of SRPA throughout the study period, i.e., on change of SRPA from baseline to six- and twelve months of the intervention, after the one-year follow-up, and during COVID-19. Wald tests were used to compare changes in SRPA from baseline to each of the subsequent time points across study groups and further in pooled data. The models included the main effects of group and time, and the group x time interaction effect. The intention-to-treat principle was followed.

Change score models

To investigate the effects of changes in EFs on concurrent and subsequent SRPA, additional latent change score models were constructed for each of the three EF variables separately and combined for the three EF variables. The EF variables were included in the model as change scores and SRPA as a nominal outcome variable. The model in presented in Figure 3 (Sub-study IV).

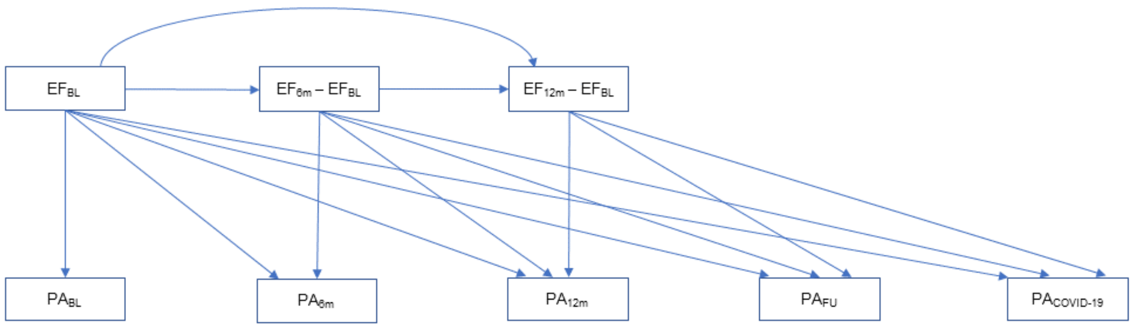

FIGURE 3 Change score model. Abbreviations: EF = Executive functions; PA = Physical activity; BL = Baseline; 6m = Measurement at six months; 12m = Measurement at twelve months; FU = One-year follow-up; COVID-19 = Extended follow-up during restrictions due to the coronavirus pandemic.

4.5.4 Missing data

In all the accelerometer-based PA analyses, mean daily values for PA outcomes were averaged over all days with ten or more hours of wear-time. Participants with two or less valid days were classified as having missing data. At baseline, 21 (7%) participants lacked accelerometry data and hence were excluded from the sample in Sub-studies I and II. Technical failure (n = 18) was the single most common reason, and three participants had insufficient wear-time. The most common reason for missing data in the longitudinal analyses of the intervention effects on accelerometer-based PA (unpublished data) was dropout. At six and twelve months, 15 (5%) and 23 (7%) participants, respectively, had dropped out. Other reasons included technical failure, insufficient use, and accelerometer not issued due to life situation, lost in the mail, or not returned. The overall proportion of missing accelerometry data was 10% at six months and 15% at twelve months. Nine (3%) participants had received a total hip replacement and hence, owing to missing DXA measurements on the proximal femur bone traits, were excluded from the sample in Sub-study II. Missing data on other outcomes were mainly due to dropout, other reasons accounting for only a minor amount (< 3%). We assumed that missing data were missing at random and therefore used the maximum likelihood estimation for incomplete data in all the GEE models and MLLPMs in Sub-study IV and for unpublished longitudinal analyses, and the maximum quasi-likelihood ratio in Sub-study III. However, the sample for the unpublished analyses on changes in accelerometer-based PA outcomes was restricted to those who had valid baseline accelerometry data.

5 RESULTS

5.1 Participant characteristics

Participant characteristics at baseline are summarized in Tables 2–3 according to the sample of Sub-studies I–IV. Table 2 presents the basic background characteristics and Table 3 the baseline characteristics related to body composition and physical capacity. Among the 284 participants who had valid accelerometer and bone measurement data and were thus included in the sample of Sub-study II, 163 (49%) had a femoral neck T-score of -1 or below, indicating osteopenia, and 11 (4%) had a T-score of -2.5 or below, indicating potential osteoporosis. Two (1%) participants used bisphosphonates and 12 (4%) oral glucocorticoids. Twenty-three (14%) of the female participants used hormone replacement therapy.

TABLE 2 Baseline characteristics of the participants in the PASSWORD study with means (standard deviations) and frequencies (percentages) as reported in Sub-studies I–IV.

Sub-study	III			IV		I	II
Subgroup	All	Men	Women	PTCT	PT		
N	314	126	188	155	159	293	284
	Mean (SD)						
Age, years	74.4 (3.8)	74.4 (3.9)	74.5 (3.8)	74.4 (3.9)	74.5 (3.8)	74.4 (3.8)	74.4 (3.8)
Height, m	1.66 (0.09)	1.74 (0.06)	1.60 (0.06)	N/A	N/A	1.66 (0.09)	1.66 (0.09)
Weight, kg	76.9 (14.2)	84.3 (12.5)	71.9 (13.1)	N/A	N/A	76.8 (14.4)	76.9 (14.4)
BMI, kg/m^2	27.9 (4.7)	27.9 (3.6)	28.0 (5.3)	28.0 (4.9)	27.9 (4.5)	27.9 (4.8)	27.9 (4.8)
	N (%)						
Women	188 (60)			96 (62)	92 (58)	171 (58)	163 (57)
Married/living with a partner	199 (63)	103 (82)	96 (51)	102 (66)	97 (61)	N/A	N/A
College/university degree	66 (21)	21 (17)	45 (24)	38 (25)	28 (18)	64 (22)	N/A
Self-rated health, good/very good	141 (45)	57 (45)	84 (45)	73 (47)	68 (43)	135 (46)	N/A
Self-rated mobility, good/very good	N/A	N/A	N/A	N/A	N/A	269 (92)	N/A
No difficulties in outdoor mobility	245 (78)	104 (82)	141 (75)	122 (79)	123 (77)	N/A	N/A
Smoking status							
Never	191 (61)	56 (44)	135 (72)	94 (61)	97 (61)	N/A	175 (62)
Former	109 (35)	61 (48)	48 (26)	52 (34)	57 (36)	N/A	98 (35)
Current	14 (4)	9 (7)	5 (3)	9 (6)	5 (3)	N/A	11 (4)

Abbreviations: PTCT = Physical and cognitive training group; PT = Physical training group; SD = Standard deviation; BMI = Body mass index.

TABLE 3 Participants' selected body composition and physical capacity characteristics with means (standard deviations) reported in Sub-studies I-III.

	Sub-study III			Sub-study I		Sub-study II	
	All	Men	Women	Men	Women	Men	Women
N	314	126	188	122	171	121	163
Fat %	36.2 (8.2) [a]	30.2 (6.0) [a]	40.1 (7.0)	30.2 (6.0) [a]	40.0 (7.0)	N/A	N/A
Appendicular lean mass, kg	19.3 (4.3) [a]	23.7 (2.9) [a]	16.4 (2.0)	23.7 (3.0) [a]	16.4 (2.0)	N/A	N/A
Bone traits							
Femoral neck BMC, g	N/A	N/A	N/A	N/A	N/A	4.967 (0.996)	4.053 (0.798)
Femoral neck BMD, g/cm^2	N/A	N/A	N/A	N/A	N/A	0.932 (0.137)	0.885 (0.124)
Total femur BMC, g	N/A	N/A	N/A	N/A	N/A	39.429 (6.588)	31.408 (5.056)
Total femur BMD, g/cm^2	N/A	N/A	N/A	N/A	N/A	1.037 (0.155)	0.962 (0.138)
Section modulus, mm^3	N/A	N/A	N/A	N/A	N/A	807.5 (162.5)	558.5 (110.4)
Minimal neck width, mm	N/A	N/A	N/A	N/A	N/A	35.5 (2.7)	30.7 (2.1)
Physical capacity							
SPPB score	N/A	N/A	N/A	10.6 (1.4)	9.9 (1.5)	10.6 (1.5)	10.0 (1.5)
Chair-stand, s	13.9 (3.5) [a]	12.6 (2.6)	14.8 (3.8) [a]	N/A	N/A	N/A	N/A
6-min walk, m	475.4 (81.7)	502.4 (89.9)	457.3 (70.3)	502.6 (90.7)	459.7 (71.3)	N/A	N/A
10-m walk, m/s	N/A	N/A	N/A	2.1 (0.4)	1.9 (0.3)	N/A	N/A
Knee-extension, kg	37.0 (12.0) [c]	47.2 (10.0) [b]	30.3 (7.6) [a]	N/A	N/A	N/A	N/A

Note: [a] Missing n = 1; [b] Missing n= 2; [c] Missing n = 3.

Abbreviations: BMC = Bone mineral content; BMD = Bone mineral density; SPPB = Short Physical Performance Battery; Chair-stand = Five-time chair-stand test time; 6-min walk = Six-minutes walking distance; 10-m walk = Maximal walking speed over ten meters; Knee-extension = Maximal isometric knee-extension strength.

5.2 Physical activity at baseline

5.2.1 Self-reported and accelerometer-based physical activity

The distribution of the SRPA categories at baseline is presented in Table 4 (unpublished data). Almost two thirds of the participants (63%) reported engaging, at most, in light activities, i.e., they selected category 0, 1, or 2. The median category was 2 for both men and women (Sub-study III).

TABLE 4 Self-reported current physical activity at baseline, n (%).

Category and description		All	Men	Women
0	I do not move more than necessary in my daily chores	43 (14)	19 (15)	24 (13)
1	I go for casual walks and engage in light outdoor recreation 1–2 times a week	83 (26)	34 (27)	49 (26)
2	I go for casual walks and engage in light outdoor recreation several times a week	72 (23)	20 (16)	52 (28)
3	I engage 1–2 times a week in brisk physical activity (e.g., yard work, walking, cycling) to the point of perspiring and some degree of breathlessness	76 (24)	33 (26)	43 (23)
4	I engage several times a week in brisk physical activity (e.g., yard work, walking, cycling) to the point of perspiring and some degree of breathlessness	39 (12)	19 (15)	20 (11)
5	I do keep-fit exercises several times a week in a way that causes rather strong shortness of breath and sweating during the activity	1 (0)	1 (1)	0 (0)
6	I participate in competitive sports and maintain my fitness through regular training.	0 (0)	0 (0)	0 (0)

Baseline accelerometer-based PA outcomes are summarized in Table 5 for participants with valid accelerometer data (n=293, Sub-study I) and for participants with both valid accelerometer-data and bone measurements (n=284, Sub-study II). Compliance with the accelerometer-wear instructions was good: the mean number of days with at least ten hours of wear-time was 6.7 and mean wear-time per day 14 hours. Participants recorded on average 10 hours per day of SB, 3.5 hours of LPA and half an hour of MVPA. The values reported in Sub-studies I and II differed slightly from each other due to differences in the sample size. The median (IQR) number of low, medium, and high impacts was 4 591 (2 103, 5 177), 347 (164, 662), and 112 (70, 181), respectively. The mean osteogenic index score was 173 (Sub-study II).

TABLE 5 Accelerometer-based physical activity at baseline, means (standard deviations).

	Sub-study I			Sub-study II		
	All	Men	Women	All	Men	Women
N	293	122	171	284	121	163
Days included	6.7 (0.8)	6.7 (0.7)	6.6 (0.8)	6.6 (0.8)	6.7 (0.7)	6.6 (0.8)
Wear time, h/d	14.1 (1.3)	14.3 (1.3)	13.9 (1.2)	14.1 (1.3)	14.3 (1.3)	13.9 (1.2)
Sedentary behavior, min/d	602 (83)	627 (81)	585 (80)	603 (82)	627 (81)	585 (79)
Light activity, min/d	210 (66)	197 (61)	220 (69)	210 (66)	197 (61)	219 (68)
Moderate-to-vigorous activity, min/d	33 (20)	33 (21)	32 (20)	33 (20)	33 (21)	33 (20)
Low impacts, no./d	N/A	N/A	N/A	3 937 (2 426)	4 017 (2 468)	3 877 (2 400)
Medium impacts, no./d	N/A	N/A	N/A	494 (463)	479 (432)	504 (487)
High impacts, no./d	N/A	N/A	N/A	157 (154)	165 (188)	151 (122)
Osteogenic index, score	N/A	N/A	N/A	173 (47)	169 (47)	176 (47)

All participants recorded some moderate-intensity activity (≥ 0.091 to < 0.414 g), but less than one in three participants had any activity exceeding 0.31 g, and only few recorded any vigorous-intensity activity (≥ 0.414 g) (Sub-study I, Figure 4B). Further detailed analyses on the associations of the intensity of physical activity with body composition and physical capacity outcomes are therefore limited to intensities of < 0.31 g. Participants accumulated most of their daily LPA at the lowest end of the intensity range, with a drastic decrease in minutes in each intensity bin within the light-intensity range. Similarly, participants spent most of their MVPA time at the lower end of the intensity range (Sub-study I, Figure 4B). Similarly, Figure 5 shows a steep decline in the mean number of daily impacts from over 5 000 in the first intensity bin (1.3 to < 1.5 g) to less than 10 impacts in the 3.1 to < 3.3 g bin, and less than one impact in the bins exceeding 6.1 g, except for the final bin, which covered all impacts exceeding 10.3 g (Sub-study II).

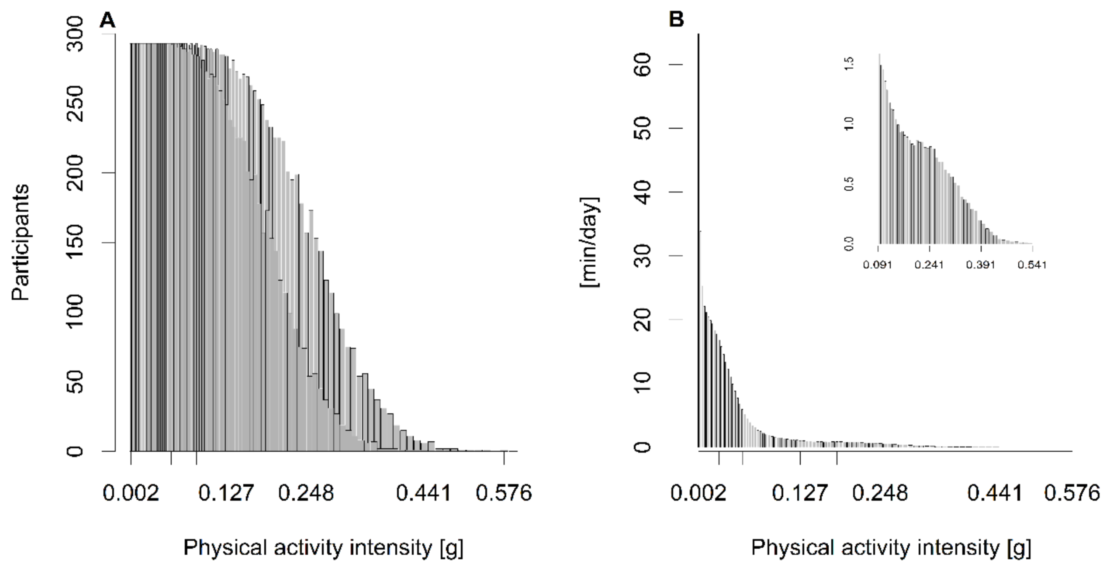

FIGURE 4 Physical activity distribution in detailed intensity ranges. A) Number of participants recording some activity in the logarithmically equidistant intensity bins along the whole intensity range. B) Mean daily minutes in the logarithmically equidistant intensity bins along the whole intensity range and within the moderate-to-vigorous-intensity activity range (≥ 0.091 g, imputed small figure).

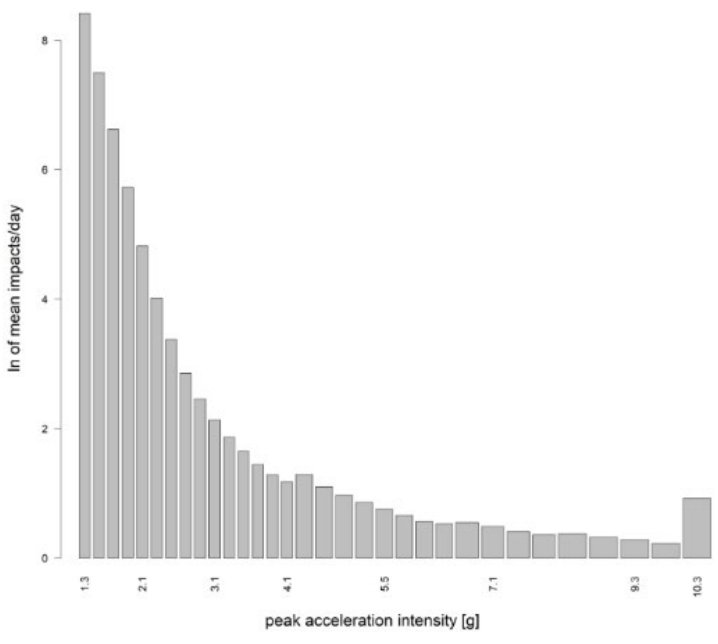

FIGURE 5 Distribution of impact peaks across the intensity range. Logarithms of the mean daily number of impacts in each of the 32 intensity bins used to calculate the osteogenic index are presented.

5.2.2 Associations between the physical activity measures

The bivariate relationships between all PA outcomes are shown in Table 6 (Sub-study II & unpublished data). Accelerometer-based SB had a weak to moderate negative relationship (r = -0.22 to -0.50) with all the other PA outcomes, whereas other accelerometer-based and self-reported PA outcomes were positively correlated with each other (r = 0.20 to 0.87). For the accelerometer-based outcomes, MVPA and impact-based outcomes showed moderate to strong associations with each other, whereas their associations with LPA were weak to moderate. SRPA showed a weak to moderate positive association with all the accelerometer-based PA outcomes.

TABLE 6 Bivariate correlations between physical activity outcomes, p-value for all associations ≤ 0.001 (n=284).

	Sub-study II[a]						Unpublished[b]
	LPA	MVPA	LI	MI	HI	OI	SRPA
SB	-0.502	-0.380	-0.368	-0.325	-0.265	-0.295	-0.238
LPA		0.319	0.441	0.342	0.296	0.373	0.290
MVPA			0.873	0.665	0.491	0.496	0.386
LI				0.724	0.542	0.547	0.352
MI					0.765	0.598	0.258
HI						0.842	0.244
OI							0.274

Note: [a] Pearson's correlation coefficient r; [b] Spearman's rho.
Abbreviations: SB = Sedentary behavior; LPA = Light intensity physical activity; MVPA = Moderate-to-vigorous intensity physical activity; LI = Low impacts; MI = Medium impacts; HI = High impacts; OI = Osteogenic index; SRPA = Self-reported current physical activity category.

5.3 Accelerometer-based physical activity, body composition, and physical capacity

5.3.1 Associations of accelerometer-based physical activity intensities with body fat, appendicular lean mass, and physical capacity

The associations of accelerometer-based PA in the intensity categories and detailed intensity ranges with the body composition and physical capacity outcomes are presented in Table 7 and Figures 6–7 (Sub-study I). Higher SB values showed a weak but statistically significant association with higher fat percent. In contrast, higher LPA and MVPA values showed a weak to moderate inverse association with body fat percent. Investigation of the detailed intensity ranges showed that higher PA of any intensity was associated with a lower body fat percent, the association becoming significantly negative already below the LPA cut-off. No statistically significant association was found between SB or PA of any intensity and appendicular lean mass.

Of the physical capacity measures, a higher SB value was related to poorer aerobic endurance, but no significant associations between SB and maximal walking speed or lower extremity functioning were observed. In contrast, higher PA of any intensity, both in intensity categories and in the detailed intensity ranges, was related to better aerobic endurance and faster maximal walking speed. The associations of MVPA with aerobic endurance and walking speed were stronger than the association of LPA with these outcomes. When investigated in the detailed intensity ranges, PA showed a statistically significant positive relationship with aerobic endurance and walking speed already below the LPA cut-off.

The relationship between PA and lower extremity functioning was less consistent. LPA and MVPA had a weak positive association with lower extremity functioning, when adjusted for sex and age. However, the association between LPA and lower extremity functioning attenuated to non-significant when adjusted further for MVPA. Investigation of the detailed intensity range revealed that the association between higher PA and better lower extremity functioning was statistically significant only at intensities above approximately 0.2 g.

TABLE 7 Pearson correlation coefficients for associations of accelerometer-based physical activity in intensity categories with body composition and physical capacity. Bold font indicates statistical significance ($p < 0.05$).

	Model 1			Model 2	
	SB	LPA	MVPA	LPA	MVPA
Body fat percent [a]	**0.251**	**-0.360**	**-0.384**	**-0.281**	**-0.312**
Appendicular lean mass [a]	0.006	-0.014	0.010	-0.018	0.015
6-min walking distance	**-0.170**	**0.279**	**0.465**	**0.168**	**0.418**
10-m walking speed	-0.101	**0.203**	**0.315**	**0.122**	**0.273**
Short Physical Performance Battery	-0.028	**0.145**	**0.220**	0.086	**0.188**

Note: Model 1: Adjusted for sex and age. Model 2: Associations with LPA adjusted for sex, age and MVPA, and associations with MVPA adjusted for sex, age, and LPA. [a] Missing n=1 Abbreviations: SB = Sedentary behavior; LPA = Light intensity physical activity; MVPA = Moderate-to-vigorous intensity physical activity.

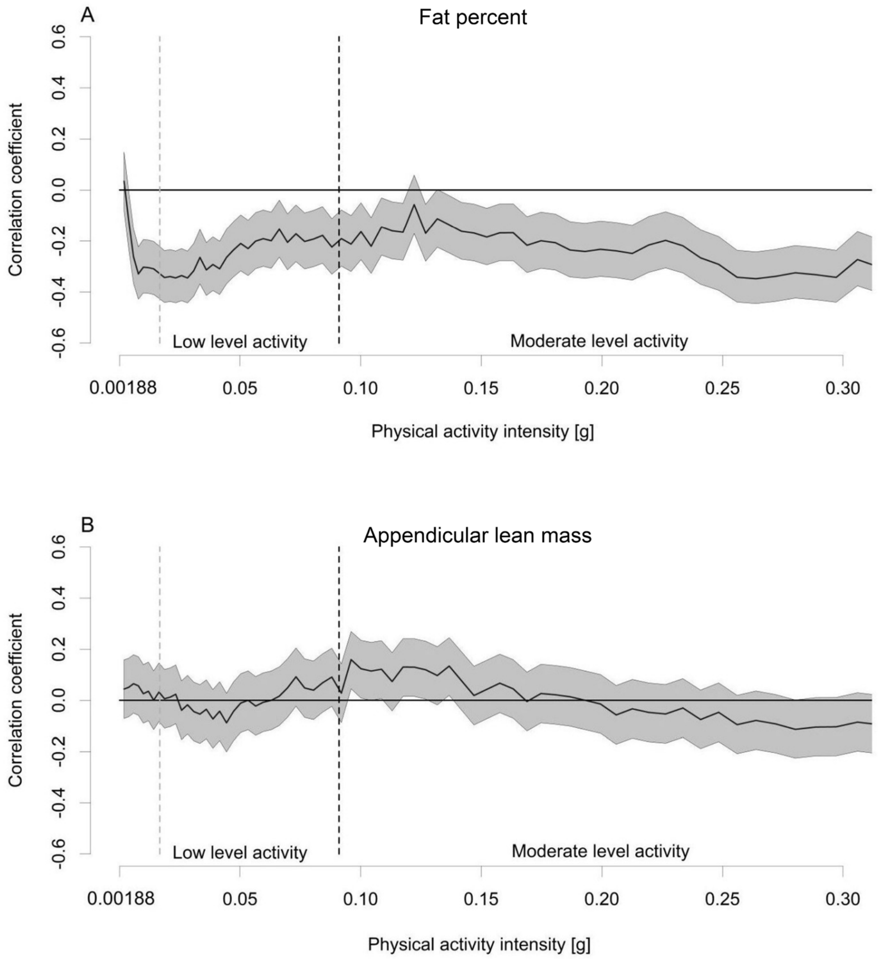

FIGURE 6 Associations of mean daily minutes in each physical activity intensity bin with A) fat percent and B) appendicular lean mass, adjusted for sex and age. Partial correlation coefficient r (black line) and 95% confidence interval (CI, shaded area) are shown. Associations are statistically significant, if the 95% CI area does not cross the 0-line. Cut-offs for light intensity physical activity (0.0167 g) and moderate intensity physical activity (0.091 g) are marked with vertical lines.

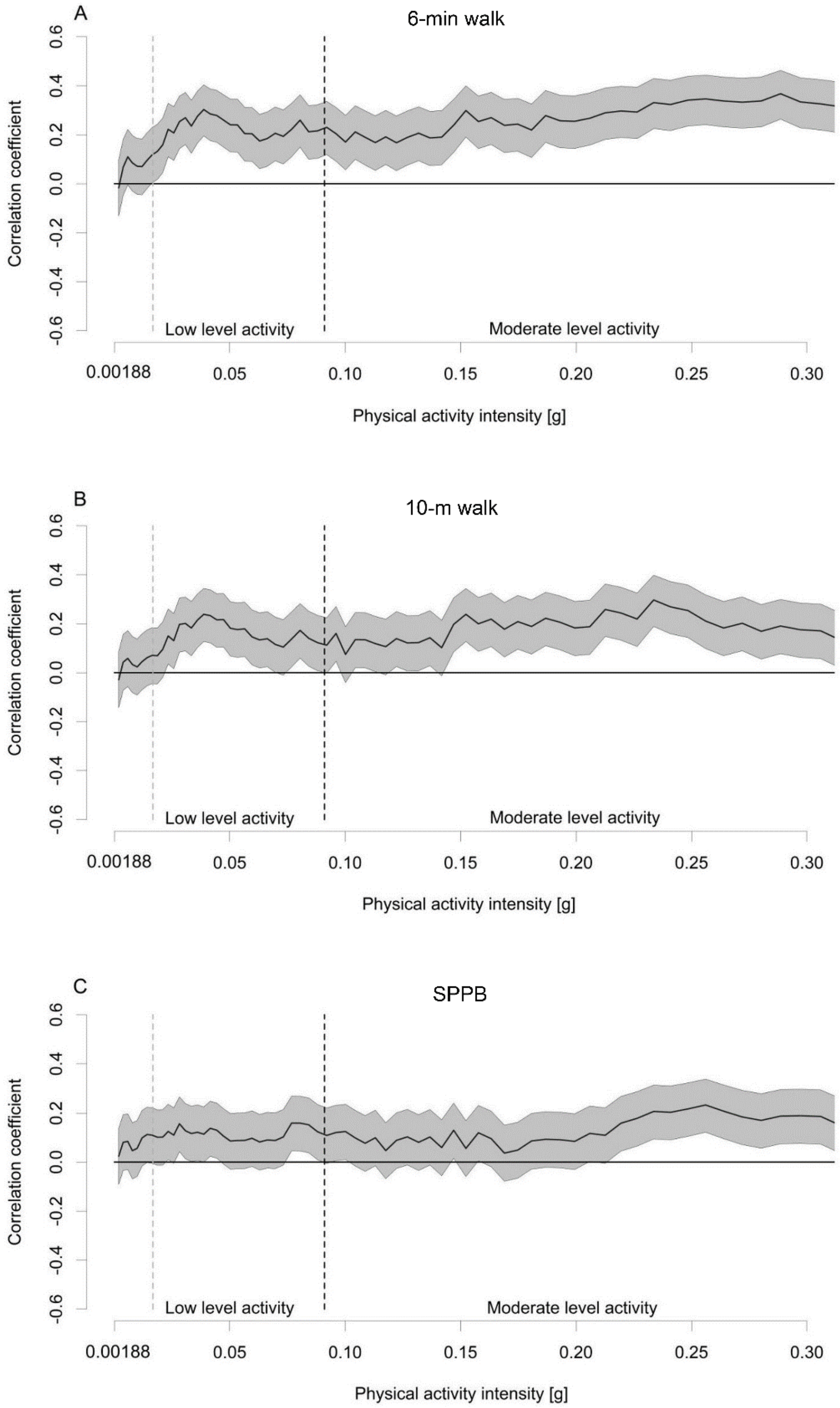

FIGURE 7 Associations of mean daily minutes in each physical activity intensity bin with A) 6-min walking distance, B) maximal walking speed over 10 m, and C) the Short Physical Performance Battery test score adjusted for sex and age. Partial correlation coefficient r (black line) and 95% confidence interval (CI, shaded area) are shown. Associations are statistically significant, if the 95% CI area does not cross the 0-line. Cut-offs for light intensity physical activity (0.0167 g) and moderate intensity physical activity (0.091 g) are marked with vertical lines.

5.3.2 Associations of accelerometer-based physical activity intensities, impact intensities, and osteogenic index with proximal femur bone traits

Table 8 presents the relationships between proximal femur bone traits and accelerometer-based PA intensities, impact intensities, and osteogenic index (Sub-study II). LPA was positively associated with BMC and BMD of the femoral neck and total femur and bending strength of the femoral neck. For example, ten minutes more daily LPA was associated with a 0.024 g increase in femoral neck BMC and 0.003 g/cm^2 increase in femoral neck BMD. The associations remained significant when further adjusted for SB and MVPA. In contrast, SB or MVPA did not have any significant relationships with proximal femur bone traits.

Low impacts were positively associated with femoral neck BMD and negatively with femoral neck width when adjusted for all covariates and other impact intensities. No other statistically significant relationships between impact volume in the intensity categories or osteogenic index and proximal femur bone traits were found. Investigation of the impacts along detailed intensity range revealed no significant associations of any impact intensity with any bone trait. Figure 8 presents the results for femoral neck BMC, BMD, and section modulus.

TABLE 8 Associations of accelerometer-based physical activity with proximal femur bone traits. Standardized beta coefficients from multiple linear regression analysis are shown. Bold font indicates a statistically significant association ($p < 0.05$).

	SB	LPA	MVPA	LI	MI	HI	OI
Model 1							
FN BMC	-0.076	**0.158**	0.055	0.078	0.048	0.030	0.046
FN BMD	-0.062	**0.165**	0.025	0.080	-0.039	-0.056	-0.009
TF BMC	-0.070	**0.148**	0.040	0.080	0.039	0.007	0.040
TF BMD	-0.083	**0.182**	0.026	0.102	0.020	-0.026	0.023
SM	-0.034	**0.147**	0.007	0.004	-0.033	-0.005	0.019
MNW	0.022	0.053	0.002	-0.062	0.008	0.024	0.008
Model 2							
FN BMC	-0.004	**0.152**	0.024	0.078	0.009	-0.010	N/A
FN BMD	0.010	**0.170**	-0.004	**0.186**	-0.102	-0.065	N/A
TF BMC	-0.005	**0.144**	0.011	0.093	0.020	-0.049	N/A
TF BMD	-0.010	**0.180**	-0.011	0.157	-0.001	-0.095	N/A
SM	0.034	**0.165**	-0.013	0.047	-0.096	0.043	N/A
MNW	0.068	0.082	0.010	**-0.117**	0.046	0.043	N/A

Note: Model 1 adjusted for sex, age, weight, height, lower extremity functioning, smoking, and use of hormone replacement therapy, bisphosphonates, and oral glucocorticoids. Model 2 further adjusted for other intensity bands, one cluster including SB, LPA, and MVPA, and the other including LI, MI, and HI.
Abbreviations: SB = Sedentary behavior; LPA = Light intensity physical activity; MVPA = Moderate-to-vigorous intensity physical activity; LI = Low impacts; MI = Medium impacts; HI = High impacts; OI = Osteogenic index; FN = Femoral neck; TF = Total femur; BMC = Bone mineral content; BMD = Bone mineral density; SM = Section modulus; MNW = Minimal neck width.

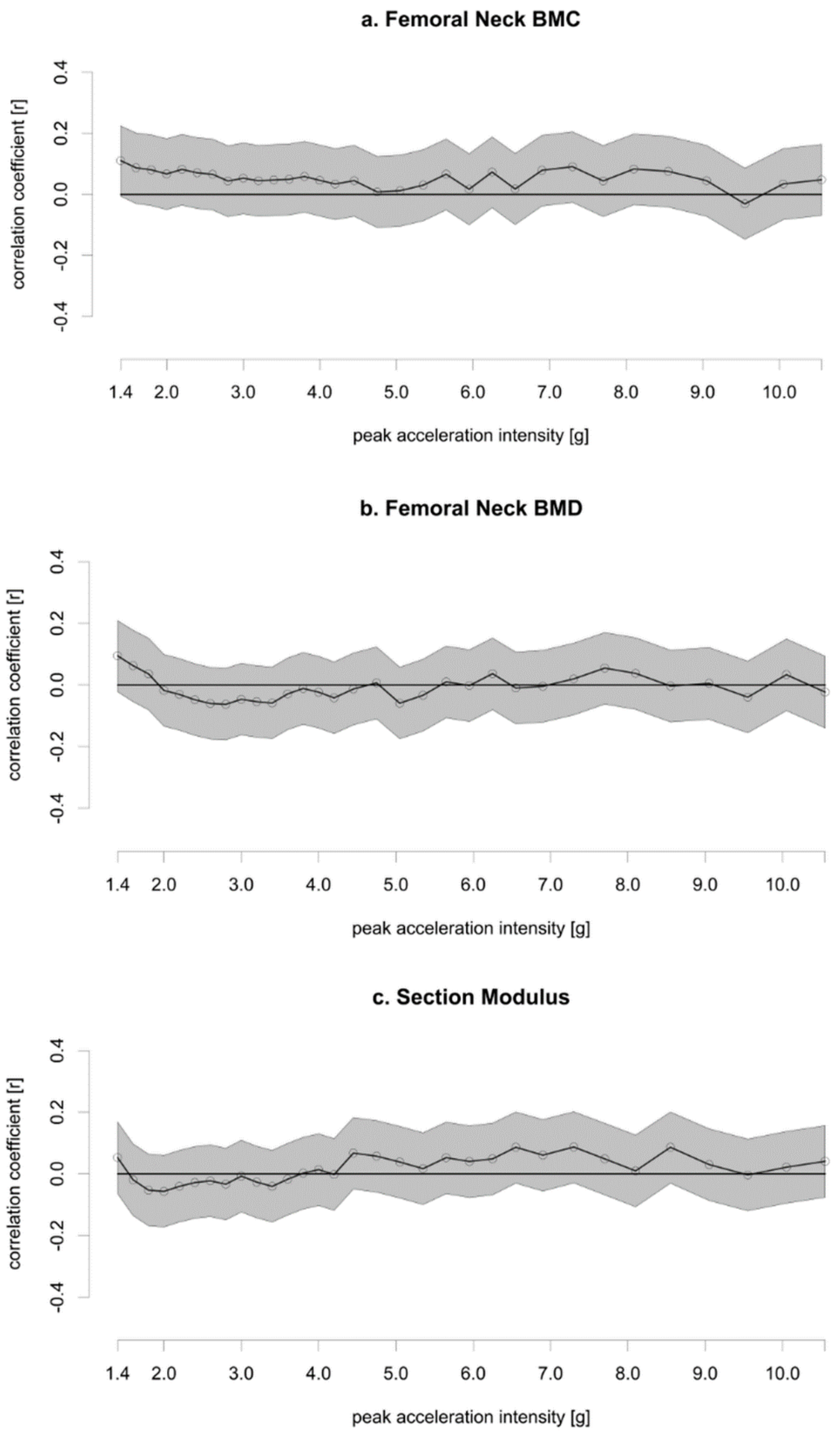

FIGURE 8 Associations of mean daily number of impacts in each intensity bin used to calculate osteogenic index with a) femoral neck bone mineral content (adjusted for weight, height, and smoking status), b) femoral neck bone mineral density (adjusted for weight, age, lower extremity functioning, and use of hormone replacement therapy), and c) section modulus (adjusted for weight, height, sex, and smoking status). Partial correlation coefficient r (black line) and 95 % confidence interval (shaded area) are shown.

5.4 Effects of year-long multicomponent training on physical activity and physical capacity

5.4.1 Adherence, attrition, and adverse events

Adherence and adverse events during the intervention were first reported by Sipilä and colleagues (2021), who found no significant differences between the participants in physical and cognitive training and physical training groups. The median proportion of supervised training sessions attended varied from 68% to 82%, the median number of weekly home-exercise sessions was 1.9, and median weekly aerobic activity was approximately 175 minutes (Sipilä et al., 2021). Forty percent of the participants reported some adverse events or symptoms, and 10% reported intervention-related adverse events or symptoms; these were mostly transient non-severe lower body muscle and/or joint pain and/or discomfort (Sub-study IV).

The attrition analyses, reported in Sub-study III, showed no differences in socio-demographic or health-related characteristics between the participants who dropped out during the intervention year and those who remained in the study. However, the attrition analyses reported in Sub-study IV showed that the participants who did not respond to the one-year follow-up questionnaire were more often in the lowest SRPA category, more often perceived difficulties in outdoor mobility, and had poorer lower extremity functioning at baseline than those who remained in the study. Participants who dropped out from the COVID-19 follow-up more often selected the lowest SRPA category, were older and had poorer lower extremity functioning at baseline than those who remained in the study. There were no differences between the study groups in retention to the study at the one-year follow-up or during COVID-19.

5.4.2 Effects of physical and cognitive training vs. physical training alone on self-reported and accelerometer-based physical activity from baseline to twelve months

Changes during the twelve-month intervention in self-reported and accelerometer-based PA outcomes did not differ between the participants in physical and cognitive training group and those in the physical training group (Figure 9). At six months into the intervention, the accelerometer-based data showed a decrease in SB of 32 minutes from the baseline value, while LPA and MVPA increased by 31 and 5 minutes, respectively, across the whole study sample (main effect of time from baseline to six months $p < 0.001$ for all). However, SB, LPA, and MVPA had all returned to their baseline levels at the twelve-month measurements (main effect of time from baseline to twelve months $p > 0.05$ for all). In contrast, an increase in SRPA was observed at both six and twelve months after intervention start (main effect of time $p < 0.001$ for both). It should be noted that accelerometer assessments were conducted after the twelve-month laboratory measurements, whereas the SRPA questionnaire was completed before the laboratory visit, but after the last supervised physical training session.

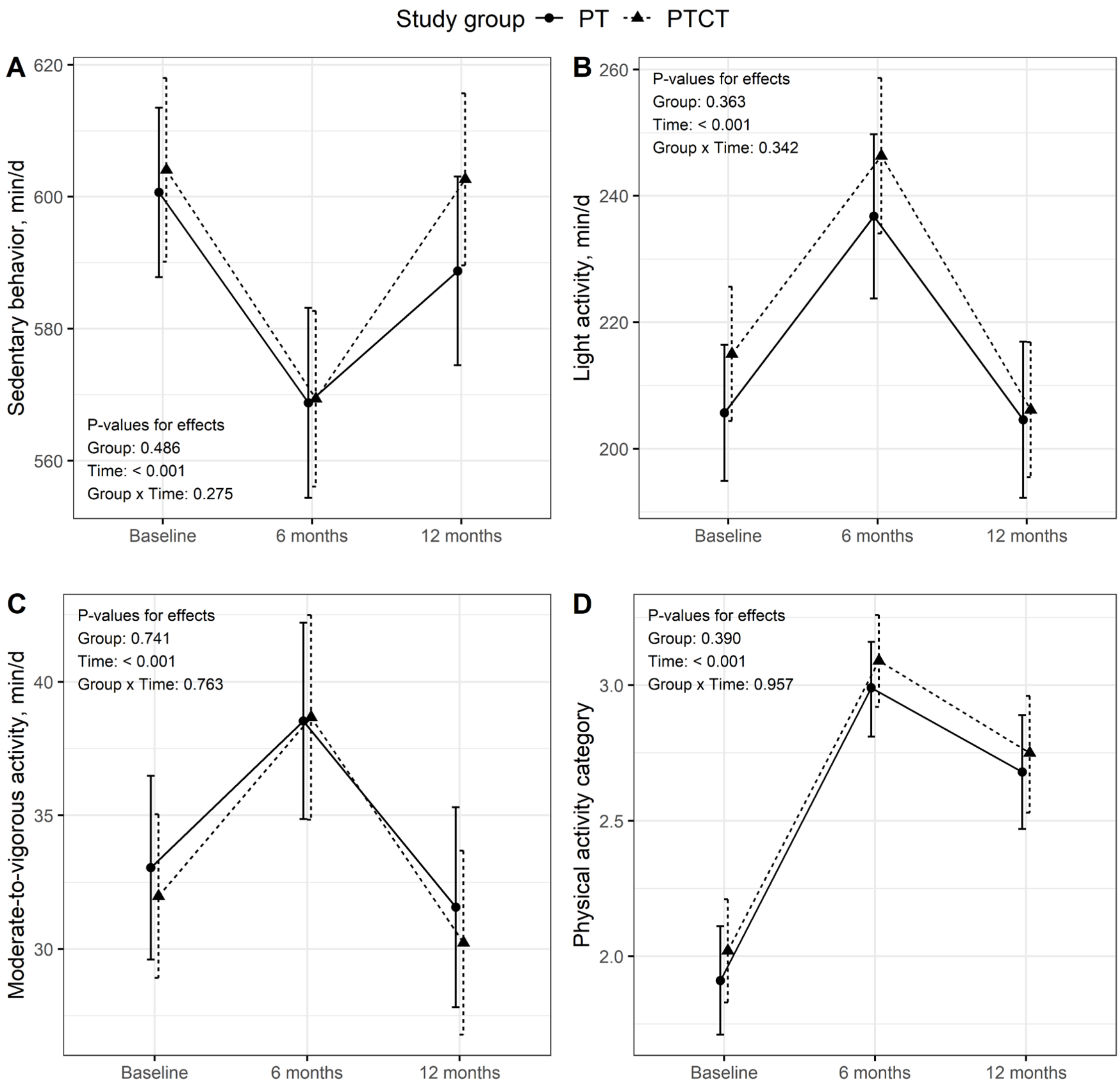

FIGURE 9 Changes in accelerometer-based A) sedentary behavior, B) light intensity physical activity, and C) moderate-to-vigorous intensity physical activity, and in D) self-reported current physical activity category (range 0–6) at six and twelve months from baseline by study group. Estimated marginal means and 95% confidence intervals from the generalized estimating equation models are shown. Abbreviations: PT = Physical training group; PTCT = Physical and cognitive training group.

5.4.3 Impact of multimorbidity patterns on the effects of multicomponent physical training on self-reported physical activity and physical capacity

Thirty-eight (12%) participants had no chronic conditions at baseline, 70 (22%) had one and 206 (66%) had two or more conditions (Sub-study III). The highest number of chronic conditions in the same individual was six. The median number of different chronic conditions was two in both men and women. Sex-specific differences in the prevalence of specific chronic conditions were observed (Table 9). Men more often had hyperlipidemia, cardiovascular disease, diabetes, and chronic urinary problems, whereas women had a higher prevalence of arthritis and/or arthrosis and thyroid disorders. Mean BMI was 27.9 (SD 4.7) kg/m^2 in both sexes.

TABLE 9 Prevalence of chronic conditions in the full study sample and by sex.

	All		Men		Women		
	N	%	N	%	N	%	p-value
Hypertension	164	52	65	52	99	53	0.908
Hyperlipidemia	127	40	61	48	66	35	0.020
Arthritis or arthrosis	72	23	18	14	54	29	0.003
Cardiovascular disease	68	22	37	29	31	16	0.008
Pulmonary disease	40	13	13	10	27	14	0.307
Chronic musculoskeletal conditions	38	12	12	10	26	14	0.292
Diabetes	38	12	22	18	16	8	0.021
Thyroid disorder	38	12	3	2	35	19	<0.001
Chronic urinary problem	30	10	27	21	3	2	<0.001
Stroke and transient ischemic attack	17	5	7	6	10	5	>0.999
Heart failure	16	5	9	7	7	4	0.198
Cancer	12	4	7	6	5	3	0.234
Depression or anxiety	10	3	2	2	8	4	0.326
Colon problem	9	3	3	2	6	3	0.745
Osteoporosis	6	2	2	2	4	2	>0.999
Stomach problem	3	1	2	2	1	0	0.567
Kidney disease or failure	2	1	2	2	0	0	0.160

Note. Fisher's exact test p-values for the difference in the prevalence of chronic conditions between men and women are shown.

As previously reported by Sipilä et al. (2021), the participants in the physical and cognitive training group and those in the physical training group showed improved aerobic endurance, muscle strength, and overall lower extremity functioning during the intervention, with no significant differences between the study groups. Multimorbidity patterns, including all chronic conditions and BMI, had a small but statistically significant impact on SRPA and each physical capacity outcome at baseline, except on muscle power among men (Sub-study III). Furthermore, the multimorbidity patterns had a statistically significant impact on the changes in SRPA and all the physical capacity outcomes over time in both men and women, with the exception of muscle power at six months in women. The time point specific effect sizes of the multimorbidity pattern x time interactions were small for both men and women, and for each outcome the explained variance in change was 3% at the maximum (Table 10).

TABLE 10 The effect of time and multimorbidity patterns on physical activity and physical capacity in men and women, adjusted for age. P-values for the effects from the fixed effects generalized estimating equation models are shown.

		Men				Women			
Effect	Time point	SRPA	6-min walk	Chair-stand	Knee-extension	SRPA	6-min walk	Chair-stand	Knee-extension
Time	6m	0.057	0.188	0.806	-	0.251	<0.001	0.122	-
	12m	0.880	0.045	0.111	0.830	0.038	0.035	0.047	0.001
	FU	0.200	-	-	-	<0.001	-	-	-
	Overall	0.070	0.011	0.167	-	<0.001	0.001	0.107	-
BMI		0.167	<0.001	0.799	0.001	<0.001	<0.001	0.539	0.277
CC		<0.001	<0.001	0.336	0.089	0.011	<0.001	0.092	0.002
BMI+CC		<0.001	<0.001	0.325	0.001	<0.001	<0.001	0.044	0.002
Time x BMI	6m	0.285	0.033	0.568	-	0.309	0.188	0.577	-
	12m	0.843	0.913	0.695	0.526	0.990	0.640	0.295	0.328
	FU	0.623	-	-	-	0.107	-	-	-
Time x CC	6m	0.064	<0.001	0.050	-	<0.001	0.018	0.229	-
	12m	0.017	0.004	<0.001	<0.001	<0.001	0.007	0.042	0.010
	FU	<0.001	-	-	-	0.047	-	-	-
Time x BMI+CC	6m	0.002	<0.001	0.050	-	<0.001	0.007	0.277	-
	12m	0.012	0.004	<0.001	<0.001	<0.001	<0.001	0.042	0.008
	FU	<0.001	-	-	-	0.002	-	-	

Note. P-values are shown for generalized estimating equation coefficients for the effects of time and BMI and their interaction, whereas p-values for effect size estimates are shown for all effects including the cluster of chronic conditions.

Abbreviations: SRPA = Self-reported current physical activity category; 6-min walk = Six-minutes walking distance; Chair-stand = Five-time chair-stand time; Knee-extension = Maximal isometric knee-extension strength; BMI = Body mass index; CC = Main effect of chronic conditions; Time x BMI = Interaction effect of time with body mass index; Time x CC = Interaction effect of time with chronic conditions; Time x BMI+CC = Interaction effect of time with body mass index and chronic conditions; 6m = Measurement at six months; 12m = Measurement at twelve months; FU = One-year follow-up.

The impact of specific chronic conditions and BMI varied according to the outcome measures, sex, and time point, and most conditions showed no consistent and/or significant impacts on any outcome over time (Tables 11 and 12). Among men, diabetes and pulmonary diseases were associated with lower baseline SRPA, but with a greater increase during the study. Of the physical capacity outcomes, arthritis/arthrosis was associated with lower baseline muscle strength and a lower increase in strength during the study. Hyperlipidemia was associated with poorer, and heart failure with better, aerobic endurance throughout the study.

Among women, pulmonary diseases were associated with higher SRPA at baseline and a lower increase during the study. Hyperlipidemia was positively associated with changes in all the physical capacity outcomes while arthritis/arthrosis showed mixed associations across the outcomes.

TABLE 11 The associations of chronic conditions with physical activity and physical capacity in men. Generalized estimating equation coefficients from the fixed effects generalized estimating equation models are shown. Bold font indicates statistical significance ($p < 0.05$).

	SRPA				6-min walk			Chair-stand			Knee-extension	
	CC	Time x CC			CC	Time x CC		CC	Time x CC		CC	Time x CC
		6m	12m	FU		6m	12m		6m	12m		12m
BMI	-0.05	-0.03	0.01	-0.02	**-8.85**	**2.65**	-0.10	0.02	-0.02	0.02	**0.70**	0.09
Hypertension	0.02	-0.29	0.07	0.13	-4.66	3.45	-1.01	0.18	0.06	-0.64	-2.08	0.84
Hyperlipidemia	-0.03	0.02	0.02	-0.16	**-35.45**	-4.22	3.20	0.30	0.39	0.22	0.68	1.22
Arthritis or arthrosis	-0.17	0.42	0.02	-0.29	-0.90	-0.46	-18.24	0.01	0.74	0.65	-2.82	**-2.83**
Cardiovascular disease	-0.04	-0.02	-0.20	-0.06	-11.27	-11.63	-10.28	-0.13	0.02	-0.50	1.85	0.79
Pulmonary disease	**-1.15**	0.48	0.66	1.09	9.39	0.58	-14.67	-0.23	-0.30	0.21	-0.42	-0.76
Thyroid disorder	-0.17	-0.23	-0.12	-0.95	-25.27	0.00	-11.41	-1.85	1.72	**1.98**	3.81	3.73
Diabetes	**-1.03**	**0.95**	**0.74**	**1.17**	-9.33	-21.59	4.60	1.46	-0.26	-0.18	0.34	-0.40
Chronic musculoskeletal conditions	-0.51	0.00	-0.22	-0.21	-12.00	19.88	**-23.42**	0.24	0.55	0.24	-2.34	-0.02
Chronic urinary problem	-0.40	0.31	0.40	0.46	16.82	5.57	-1.38	-0.50	0.05	0.22	0.44	-1.13
Stroke and transient ischemic attack	0.15	0.67	0.56	0.44	-23.90	17.18	9.19	0.44	-0.33	-0.16	3.35	-1.64
Heart failure	0.01	0.19	0.30	0.67	**30.85**	53.02	15.34	-0.59	-0.70	-0.62	-0.88	1.23
Cancer	**0.53**	-0.36	-0.27	-0.57	33.81	7.70	-15.57	-0.94	0.27	-0.89	4.99	-1.47
Depression or anxiety	0.43	0.38	**-0.84**	-0.51	**-91.20**	**34.21**	11.98	**3.56**	-1.67	**-3.62**	-5.10	-1.13
Colon problem	-0.31	0.28	-0.11	**1.47**	-47.72	-10.44	**73.20**	-0.21	-0.04	-0.14	-1.66	**3.12**
Osteoporosis	0.17	0.45	0.10	**1.68**	-174.43	17.31	**35.27**	1.25	1.36	-0.10	-5.29	0.93
Kidney disease or failure	0.20	-0.15	-0.08	-0.29	29.11	16.95	-13.01	-1.71	0.89	**2.35**	**-7.90**	**4.43**
Stomach problem	0.38	-0.24	0.20	1.80	6.63	**43.56**	**75.47**	-0.88	-1.45	**-2.64**	-0.23	**9.26**

Abbreviations: SRPA = Self-reported current physical activity category; 6-min walk = Six-minutes walking distance; Chair-stand = Five-time chair-stand time; Knee-extension = Maximal isometric knee-extension strength; CC = Main effect of chronic condition; Time x CC = Interaction effect of time with chronic conditions; 6m = Measurement at six months; 12m = Measurement at twelve months; FU = One-year follow-up; BMI = Body mass index.

TABLE 12 The associations of chronic conditions with physical activity and physical capacity in women. Generalized estimating equation coefficients from the fixed effects generalized estimating equation models are shown. Bold font indicates statistical significance ($p < 0.05$).

	SRPA				6-min walk			Chair-stand			Knee-extension	
	CC	Time x CC			CC	Time x CC		CC	Time x CC		CC	Time x CC
		6m	12m	FU		6m	12m		6m	12m		12m
BMI	**-0.05**	0.02	0.00	-0.03	**-5.18**	-0.72	-0.46	0.03	0.02	0.06	0.11	-0.06
Hypertension	0.04	-0.08	-0.18	-0.08	-10.20	-14.58	-7.38	0.86	-0.18	-0.11	-0.37	-0.10
Hyperlipidemia	-0.16	0.30	0.39	0.25	13.93	-4.78	15.93	-0.01	**-0.69**	-0.31	-0.78	**1.59**
Arthritis or arthrosis	0.02	0.09	**-0.49**	0.23	**-19.67**	-13.43	-12.92	1.19	**-0.96**	**-1.41**	**-2.27**	0.00
Cardiovascular disease	-0.15	-0.19	0.02	-0.01	-7.24	**-20.66**	9.97	0.16	0.22	1.25	1.39	**-2.54**
Pulmonary disease	**0.54**	**-0.60**	**-0.77**	**-0.86**	-9.70	-6.97	-18.59	-0.28	-0.05	0.06	-1.72	0.54
Thyroid disorder	-0.18	0.19	0.17	-0.11	-1.01	2.21	-0.57	-0.88	0.21	-0.11	-1.00	0.79
Diabetes	0.30	-0.23	-0.34	-0.32	-2.37	**21.21**	0.75	-0.46	-0.23	**-1.24**	0.80	-0.48
Chronic musculoskeletal conditions	-0.29	-0.17	-0.14	-0.31	-11.92	16.13	-21.73	1.56	-0.08	-0.40	-1.40	-0.68
Chronic urinary problem	**-0.97**	-0.59	**-0.97**	**-0.72**	-32.13	**20.80**	-32.15	2.84	1.87	0.29	-5.72	**6.28**
Stroke and transient ischemic attack	-0.07	0.14	-0.30	-0.14	-22.06	-4.65	**-29.02**	-0.70	0.53	**1.68**	-0.57	-1.15
Heart failure	0.27	0.23	0.19	-0.33	14.35	17.44	-3.41	**-2.45**	0.03	0.60	-1.06	-1.30
Cancer	0.15	0.09	-0.12	-0.15	21.74	-6.75	-15.49	-0.78	0.15	0.28	**5.47**	**-3.48**
Depression or anxiety	0.39	-0.42	-1.00	-0.46	29.12	-13.62	-10.58	-0.26	-0.66	-1.34	**6.43**	-0.20
Colon problem	-0.08	-0.41	**-0.86**	-0.36	**-81.54**	24.99	15.24	1.67	-1.15	-1.43	-4.30	1.01
Osteoporosis	-0.39	**0.91**	0.60	**1.25**	41.81	2.47	22.86	-1.26	0.71	-0.77	3.14	0.64

Abbreviations: SRPA = Self-reported current physical activity category; 6-min walk = Six-minutes walking distance; Chair-stand = Five-time chair-stand time; Knee-extension = Maximal isometric knee-extension strength; CC = Main effect of chronic condition; Time x CC = Interaction effect of time with chronic conditions; 6m = s Measurement at ix months; 12m = Measurement at twelve months; FU = One-year follow-up; BMI = Body mass index.

5.4.4 Effects of physical and cognitive training on self-reported physical activity at one-year follow-up and during COVID-19 compared to physical training alone

SRPA changed significantly over time in both study groups and was above baseline values at both the one-year follow-up and during COVID-19 (Figure 10 and Table 13, Sub-study IV). Further investigation of the data from the whole study sample revealed that 46% and 56% of the participants reported a higher SRPA category after the one-year follow-up and during COVID-19, respectively, than at baseline. The proportion of participants who reported engaging in brisk activity or keep fit exercise several times per week was 29% after the one-year follow-up and 43% during COVID-19, compared to 13% at the baseline.

TABLE 13 The effects of physical and cognitive training vs. physical training alone on change in self-reported physical activity. Regression coefficient estimates of the effect and standard errors (SE) from multinomial logistic longitudinal path model are shown.

Effect	Parameterization	Estimate	SE	P-value for Wald test	
				Overall	Time point specific
Group	PTCT – PT	-0.08	0.34	0.801	
Time				<0.001	
	6m – BL	1.61	0.29		<0.001
	12m – BL	1.34	0.29		<0.001
	FU – BL	0.72	0.30		0.018
	COVID-19 – BL	1.50	0.29		<0.001
Group × Time				0.616	
	$PTCT_{6m - BL} - PT_{6m - BL}$	0.16	0.41		0.690
	$PTCT_{12m - BL} - PT_{12m - BL}$	0.11	0.42		0.791
	$PTCT_{FU - BL} - PT_{FU - BL}$	0.59	0.43		0.171
	$PTCT_{COVID\text{-}19 - BL} - PT_{COVID\text{-}19 - BL}$	0.28	0.42		0.502

Note. The highest physical activity category is the reference category.
Abbreviations: PTCT = Physical and cognitive training group; PT = Physical training group; BL = Baseline; 6m = Measurement at six months; 12m = Measurement at twelve months; FU = One-year follow-up; COVID-19 = Extended follow-up during restrictions due to the coronavirus pandemic.

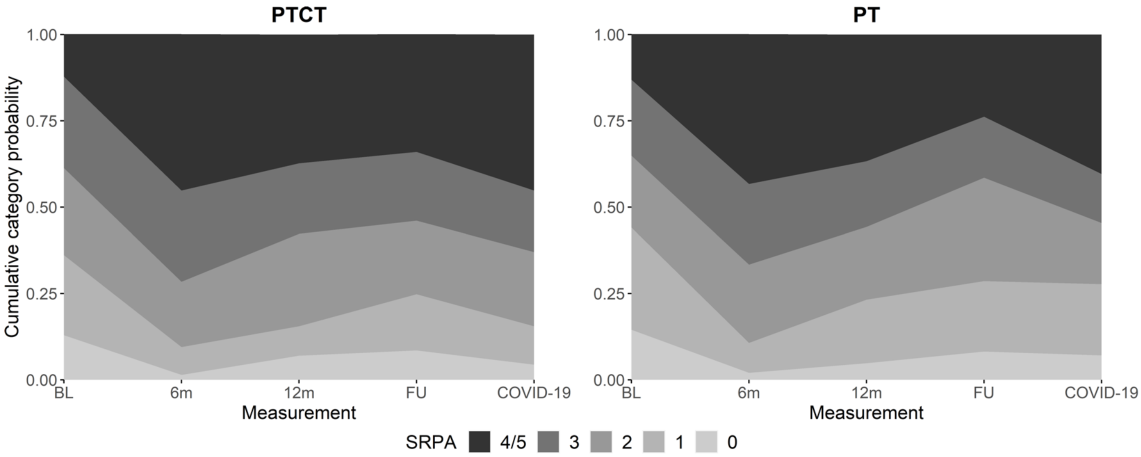

FIGURE 10 Change in physical activity category selection probability over time by study group. Abbreviations: PTCT = Physical and cognitive training group; PT = Physical training group; BL = Baseline; 6m = Measurement at six months; 12m = Measurement at twelve months; FU = One-year follow-up; COVID-19 = Extended follow-up during restrictions due to the coronavirus pandemic; SRPA = Self-reported physical activity category as follows: 0) No more than necessary; 1) Casual walks/light outdoor recreation 1-2 times a week; 2) Casual walks/light outdoor recreation several times a week; 3) Brisk physical activity 1-2 times a week; 4/5) Brisk physical activity or keep fit exercise several times a week.

5.4.5 Executive functions predicting self-reported physical activity during and after physical and cognitive training

The participants in the physical and cognitive training group improved in their response inhibition ability more than peers in the physical training group, whereas no group x time interactions were observed for cognitive flexibility or working memory, as reported by Sipilä and colleagues (2021). Working memory improved in both study groups, but the improvement in cognitive flexibility was statistically significant only in the combined training group (Sipilä et al., 2021). In the present study, we investigated, first, the combined effect of all three aspects of EFs on SRPA. The results showed that the interaction effect of joint EFs and study group on SRPA was not statistically significant, thus indicating a similar effect in both study groups (Table 14, Sub-study IV). There was a trend towards joint EFs predicting SRPA when all the participants' data were pooled. Further investigation of all three EF tests separately revealed that response inhibition and cognitive flexibility had a similar predictive effect on SRPA in both study groups. In contrast, the interaction effect of working memory and group on SRPA was significant, indicating different effects between the physical and cognitive training group and the physical training group. The predictive effect of working memory on SRPA was significant only in the two-group model, in which the effects were investigated separately for each study group, but not in the pooled data. Therefore, the time point specific effects of response inhibition and cognitive flexibility on SRPA were investigated further using the pooled data, while for working memory we examined the effects in both study groups separately.

TABLE 14 Tests on effect constraints for executive functions on self-reported physical activity. P-values for Wald chi-square test are shown.

	Two groups		Pooled data
	EF → SRPA	EF × group → SRPA	EF → SRPA
Joint executive functions	0.070	0.138	0.055
Stroop incongruent – congruent	0.032	0.384	0.003
Trail Making Test B–A	0.072	0.371	0.040
Letter Fluency	0.016	0.026	0.064

Note: Joint executive functions tested the joint effects of the Stroop, Trail Making Test B-A and Letter Fluency tests.
Abbreviations: EF = Executive functions; SRPA = Self-reported current physical activity category.

Table 15 summarizes the results for EFs predicting SRPA. No aspect of the baseline EFs predicted baseline SRPA ($p \geq 0.21$ for all). In the pooled data, better baseline response inhibition ability predicted a lower probability of selecting a low SRPA category, i.e., it predicted higher SRPA, at all subsequent time points (p ranged from 0.015 to 0.030). Better baseline cognitive flexibility predicted higher SRPA at six months and during COVID-19 ($p = 0.006$ and 0.030, respectively). Changes in response inhibition or cognitive flexibility during the intervention did not show a statistically significant predictive effect on SRPA, although a trend was observed towards greater changes in response inhibition from baseline to six months predicting a higher SRPA category at six- and twelve-month measurements and at one-year follow-up ($p = 0.087$–0.089).

For working memory, we found significant predictive effects on SRPA only in the physical training group: better baseline working memory predicted higher SRPA at twelve months and at the one-year follow-up ($p = 0.030$ and 0.002, respectively). In addition, greater overall change in working memory predicted higher SRPA at twelve months ($p = 0.020$).

TABLE 15 The predictive effect of executive functions on self-reported physical activity. Regression coefficient estimates (standard errors) from multinomial longitudinal change score models are shown. Bold font indicates statistical significance ($p < 0.05$).

	Baseline	6 months	12 months	One-year follow-up	COVID-19
Pooled data					
Stroop					
Baseline	0.000 (0.004)	**0.011 (0.005)**	**0.013 (0.005)**	**0.013 (0.006)**	**0.013 (0.006)**
Change at 6 months		0.011 (0.006)	0.012 (0.007)	0.012 (0.007)	0.010 (0.007)
Change at 12 months			0.006 (0.008)	0.006 (0.008)	0.003 (0.009)
TMT B–A					
Baseline	0.001 (0.002)	**0.007 (0.002)**	0.003 (0.002)	0.003 (0.002)	**0.005 (0.002)**
Change at 6 months		0.001 (0.003)	-0.002 (0.003)	-0.002 (0.004)	0.003 (0.004)
Change at 12 months			-0.001 (0.003)	0.003 (0.003)	-0.002 (0.003)
Two-group model					
Letter Fluency					
PTCT					
Baseline	0.013 (0.011)	-0.011 (0.012)	-0.005 (0.012)	0.001 (0.012)	-0.009 (0.013)
Change at 6 months		-0.007 (0.018)	-0.027 (0.020)	-0.022 (0.021)	0.001 (0.021)
Change at 12 months			0.015 (0.019)	0.010 (0.020)	-0.003 (0.020)
PT					
Baseline	-0.010 (0.010)	-0.019 (0.013)	**-0.028 (0.013)**	**-0.042 (0.013)**	-0.020 (0.013)
Change at 6 months		0.038 (0.024)	0.040 (0.028)	0.006 (0.026)	0.002 (0.027)
Change at 12 months			**-0.054 (0.023)**	-0.006 (0.022)	0.007 (0.023)

Abbreviations: Stroop = Stroop incongruent – Stroop congruent (response inhibition); TMT B–A = Trail Making Test B – Trail Making Test A (cognitive flexibility); Letter Fluency = Letter Verbal Fluency test (working memory); PTCT = Physical and cognitive training group; PT = Physical training group.

6 DISCUSSION

This dissertation research showed that community-dwelling older adults who reported not meeting the physical activity recommendations, accumulated most of their activity at very low intensities and a minimal amount of high intensity activity measured both as intensity minutes and as impact counts. Their physical activity was positively associated with several body composition and physical capacity outcomes, although the magnitude and direction of the association varied across the different physical activity and outcome measures. Physical activity showed the strongest and most consistent associations with lower fat percent, aerobic endurance, and faster walking speed, whereas the relationships with bone traits, lean mass and lower extremity functioning were more inconsistent and/or non-significant. Furthermore, the results showed that a year-long multicomponent physical training intervention with or without a cognitive training component led to increased physical activity from baseline to mid-intervention. Although accelerometer-based physical activity had returned to its baseline level at the twelve-month measurements, self-reported physical activity remained above the baseline level throughout the study period, including at the one-year follow-up and thereafter during the COVID-19 restrictions. Although cognitive training targeting executive functions did not provide additive effects over physical training alone, better baseline executive functions, especially response inhibition, were associated with a higher increase in and better maintenance of physical activity during and after the intervention. In this study, multimorbidity did not have a notable impact on the effects of the multicomponent physical training among relatively well-functioning older adults. Multimorbidity patterns explained 3% at most of the variation in the change in each physical activity and capacity outcome during the study.

6.1 Physical activity at baseline

In this study, two thirds of the participants reported engaging in, at most, low-intensity activity, with only one in eight participants reporting engagement in brisk activity or keep-fit exercise several times per week, before the intervention started. However, the average amount of accelerometer-based moderate-to-vigorous activity at baseline was already relatively high – more than half an hour per day. While slightly less than the amount observed among Finnish older adults in previous studies utilizing similar MAD-based processing of raw acceleration data (Gao et al., 2020; Husu et al., 2016; Iso-Markku et al., 2018; Kujala et al., 2019), it meets the current physical activity recommendation, according to which all activity counts towards the target of at least 150 minutes of moderate activity per week (Bull et al., 2020; Piercy et al., 2018). It should be noted that the physical activity recommendations at the time of the data collection emphasized that moderate-to-vigorous activity should be accumulated in bouts of at least ten continuous minutes (Nelson et al., 2007) and that the volume of activity in such bouts was well below the recommended minimum of 2.5 hours per week, i.e., 80 and 86 minutes in the physical and cognitive training group and the physical training group, respectively (Sipilä et al., 2021). The mean volume of light physical activity – 2.5 hours per day – was comparable to that found in previous studies of Finnish older adults (Gao et al., 2020; Husu et al., 2016; Iso-Markku et al., 2018; Kujala et al., 2019).

This study contributes to the previous literature by providing novel information on how physical activity is distributed along the whole intensity range. The results showed that most of the mean daily activity was accumulated at very low intensities. This was seen in both physical activity minutes and the number of impacts in intensity bins along the intensity ranges. Less than one third of the participants recorded any activity exceeding 0.31 g, which corresponds to brisk walking at approximately 5 km/h (Vähä-Ypyä, Vasankari, Husu, Mänttäri, et al., 2015), and the amount of vigorous activity was virtually non-existent. A similar trend was observed for impacts: the mean daily number of impacts was less than ten in each bin over 3 g, which corresponds to steps during very brisk walking or slow jogging (Vainionpää et al., 2006). It was important to investigate these distributions separately, since the rare high-intensity impacts are attenuated when physical activity intensity is averaged over longer bouts, such as one-minute epochs (Deere et al., 2016).

Impact-based measures have been little studied in older adults. In general, the impact accumulation pattern resembled that observed by Ahola and colleagues (2010) in working-age people, although the number of impacts was lower throughout the intensity range, resulting in a markedly lower osteogenic index score. While a few previous studies have investigated the volume of impacts in a specific number of impact intensity categories among older adults (Hannam, Deere, Hartley, Clark, et al., 2017; Tobias, 2014), they have not included an osteogenic index or impact counts along the intensity range. In the present study, comprising relatively healthy and well-functioning older men and women, the number of high-intensity impacts classified as per Deere and colleagues (2016) was notably greater than in the few previous studies conducted among comparable cohorts of older adults (Hannam, Deere, Hartley, Al-Sari, et al., 2017; Hannam, Deere, Hartley, Clark, et al., 2017).

This study contributes knowledge on the relationships between self-reported physical activity and different accelerometer-measured outcomes based on physical activity intensities and impact intensities. In line with previous findings (Kowalski et al., 2012; Skender et al., 2016), self-reported physical activity showed relatively weak associations with accelerometer-based physical activity. This is reasonable, since the single-item global questionnaire and accelerometer data captured different aspects of physical activity. It is plausible that the context and wording of the physical activity questionnaire mainly captured exercise-related physical activity, whereas accelerometers recorded physical activity in daily living. Moreover, the two methods did not cover the same time period: the questionnaire referred to *physical activity at the moment*, which can be interpreted in different ways, whereas the accelerometers recorded activity within a given timeframe after collecting the self-reported data. Furthermore, the results, especially those showing weak relationships between self-reported physical activity category and light-intensity activity on the one hand and higher-intensity impacts on the other are reasonable, since accelerometers are superior to self-report tools in their ability to capture low-intensity, incidental and intermittent habitual activity (e.g., Nigg et al., 2020; Strath et al., 2013; Vähä-Ypyä, Vasankari, Husu, Suni, et al., 2015). Interestingly, very strong correlations were found between moderate-to-vigorous activity and low impacts as well as between high impacts and the osteogenic index. Thus, while low impacts corresponded to the intensity of relatively brisk walking, high impacts very strongly influenced the total osteogenic index score in this population, making these outcomes interchangeable. Therefore, novel accelerometer-based metrics capturing the full spectrum of physical activity intensity and short bursts of impact activity provide valuable information on older adults’ habitual physical activity.

6.2 Associations of physical activity with body composition and physical capacity

Physical activity of any intensity was associated with lower body fat in the present study. This accords with previous research suggesting that accelerometer-based total and moderate-to-vigorous physical activity is associated with lower body fat in older adults (Galmes-Panades et al., 2019, 2021; Sabia et al., 2015). Investigating the associations across the whole intensity range was a novel approach and revealed that physical activity was associated with lower body fat already below the cut-off for light-intensity activity. This finding parallels that of another recent study showing a beneficial association between very low intensity activity and a more favorable cardio-metabolic risk profile in older adults (Dempsey et al., 2022). Physical activity is traditionally defined as any bodily movement resulting in energy expenditure of at least 1.5 times of the resting level (Caspersen et al., 1985). Physical activity may counteract fat gain (Villareal et al., 2005), but even activities resulting in less than 1.5 times greater energy cost compared to resting state contribute to daily energy expenditure. Since low-intensity activities comprise a large part of older adults' energy expenditure (Füzéki et al., 2017), a high volume of very light-intensity activities may counteract fat gain. Given that excess body fat is an important cardio-metabolic risk factor (Ortega et al., 2016), these findings indicate that even very low intensity physical activity may be beneficial for older adults' cardio-metabolic health.

It may also be that the present light-intensity activity cut-off was too high to reliably distinguish sedentary behavior from standing activities, which result in higher energy expenditure. A recent study utilizing a similar accelerometer-data processing approach to that of the present study showed that the optimal cut-off to distinguish sedentary and standing activities in children was as low as 0.0033 g (Gao et al., 2019) compared to the 0.0167g generally applied in studies among adults and older adults (Gao et al., 2020; Husu et al., 2016; Iso-Markku et al., 2018; Kujala et al., 2019). It should be noted, however, that the MAD-based processing of raw acceleration data is based on movement intensity and is thus unable to identify posture, e.g., differentiate sitting from standing still. Applying other raw accelerometer data processing approaches developed for posture detection would have complemented the MAD-based data. Furthermore, since the energy cost of, e.g., walking increases with increasing age (K. S. Hall et al., 2013), activity intensity may be underestimated when cut-offs validated among younger people are applied to older adults. Hence, due to potentially too high cut-offs, the relatively weak negative association between sedentary time and higher body fat in the present study may be an underestimation.

The present results showed no significant associations between appendicular lean mass and physical activity of any intensity. Although muscle tissue is sensitive to loading induced by physical activity (Cartee et al., 2016; Distefano & Goodpaster, 2018) and other studies have found a positive relationship between accelerometer-based physical activity outcomes and lean mass in older adults (Galmes-Panades et al., 2019, 2021; Sánchez-Sánchez et al., 2019; Scott et al., 2021), this null finding is reasonable. Resistance training, especially with heavy loads, is suggested to be the most effective type of physical activity to maintain and improve muscle mass, including in older age (Csapo & Alegre, 2016; Landi et al., 2014). A known limitation of accelerometers is that they are unable to accurately capture non-impact physical activity, such as resistance training (Schrack et al., 2016). Furthermore, engagement in regular resistance training was an exclusion criterion in the present study. It is thus likely that, in general, the recorded physical activity did not include high-intensity muscle-strengthening activity.

This study is one of the first to investigate the associations between accelerometer-based physical activity, especially impact-based measures, with proximal femur bone traits among older adults. It has been suggested that high intensity dynamic activity is required to generate sufficiently strong signals to promote bone strength (Turner & Robling, 2005) and that this kind of activity is inadequately captured with traditional physical activity intensity measures (Deere et al., 2016). Hence, impact-based measures, especially high-impact counts and the osteogenic index, were expected to be better predictors of bone traits than the intensity categories of physical activity. High-impact counts and osteogenic indices have been positively associated with bone traits in the few previous studies conducted in older (Hannam, Deere, Hartley, Al-Sari, et al., 2017) and younger adults (Ahola et al., 2010; Vainionpää et al., 2006). However, in the present study, only low-impact counts were significantly associated with some of the proximal femur bone traits, while the other impact-based measures were associated with none of these traits. Interestingly, light intensity but not moderate-to-vigorous intensity activity was consistently and positively associated with most of the proximal femur bone traits. This finding contrasts with previous findings among older adults of either no significant associations between any physical activity intensity and bone traits or significant positive associations only for moderate-to-vigorous but not light activity (Gába et al., 2012; Gerdhem et al., 2008; Johansson et al., 2015; Langsetmo et al., 2020).

A few possible explanations for the discrepancy between the present and previous results can be suggested. First, the cut-off for high impacts utilized in the present study and in other studies conducted among older adults (Deere et al., 2016; Hannam, Deere, Hartley, Al-Sari, et al., 2017; Hannam, Deere, Hartley, Clark, et al., 2017) was notably lower than that considered as osteogenic in younger adults (Vainionpää et al., 2006). Thus, although it has been proposed that the intensity required to create sufficient strains for osteogenesis decreases with increasing age (Stiles et al., 2015), it is possible that the threshold applied was too low. While the osteogenic index has not previously been studied in older people, the present score correlated very strongly with the volume of high impacts and was lower than has been found in younger adults (Ahola et al., 2010). The low volume of high-intensity impacts may explain the null findings on the association of high impacts and the osteogenic index with bone traits in the present study. A second potential explanation is the use of DXA to measure bone traits. It has been suggested that DXA is not as precise in assessing bone mass in older adults as it is in younger people (Laskey, 1996). The single previous comparable study included other imaging technologies, and the positive associations found between high impacts and bone traits were not consistent across the DXA-measured outcomes (Hannam, Deere, Hartley, Al-Sari, et al., 2017). A few possible explanations can also be suggested for the unexpected positive correlation between light activity and several proximal femur bone traits observed in the present study. First, preferred activity intensity tends to decline with increasing age (DiPietro, 2001). Participants with a high volume of light activity may have engaged in higher intensity activities earlier in their lives and thus attained good bone health. Second, it may be that a high volume of upright ambulatory activities protects bone tissue from going into disuse mode (Frost, 1994). Light activities may thus counteract bone loss when the volume of high-intensity activity is low.

On the physical capacity outcomes, this study showed a consistent association between more physical activity of any intensity and faster walking speed over both short and long distances. This result is in line with earlier findings showing a positive relationship between moderate-to-vigorous, and in some cases also light, activity with walking speed (e.g., Edholm et al., 2019; Jantunen et al., 2016; Lerma et al., 2018). The positive relationship between accelerometer-based physical activity and walking is reasonable for several reasons. Walking is the most common type of physical activity among Finnish older adults (Wennman & Borodulin, 2021), and performance in walking tests assessing community walking over long distances and in fast walking, such as is required in crossing the street, is sensitive to everyday walking activities. Walking is also well captured by accelerometers (Strath et al., 2012). It is noteworthy that the correlation between physical activity and both maximal walking speed and six-minute walking distance became significantly positive well below the traditional cut-off for light intensity activity. As discussed with respect to the relationship between physical activity and body fat, it is plausible that the cut-off utilized was too high. These results indicate that even very low intensity upright ambulatory activities may support older adults' walking ability.

The relationship between accelerometer-based physical activity and overall lower extremity functioning was not as strong as the association with walking speed. Consistently significant associations were seen only at the higher end of the intensity range. Previous research has shown a positive relationship between moderate-to-vigorous activity and other composite physical function tests but mixed results for light activity (e.g., Edholm et al., 2019; Jantunen et al., 2016; Lerma et al., 2018). One explanation for this weak association may lie in the SPPB test battery used in the present study. The SPPB has been criticized for having a ceiling effect and not being able to differentiate highly functioning older adults (Puthoff, 2008). Most of the present participants were relatively well-functioning. Furthermore, as discussed earlier in connection with lean mass, accelerometers are also limited in their capability to accurately capture activity types such as yoga and resistance training that may also improve balance and muscle power (Schrack et al., 2016), both of which are assessed in the SPPB in addition to walking speed.

6.3 Effects of the physical and cognitive training intervention and the factors associated with the intervention effects

This study is the first to investigate the additive effects of physical and cognitive training over physical training alone on physical activity among physically inactive older adults. Previous research has suggested that higher executive functions facilitate physical activity (e.g., Best et al., 2014; Daly et al., 2014; P. A. Hall & Fong, 2015), and that combined physical and cognitive training is more effective in improving executive functions than physical training alone (Malmberg Gavelin et al., 2021). It was, therefore, expected that the participants in the combined training group, who on average improved more in inhibitory control than those in the physical training group (Sipilä et al., 2021), would also show a greater increase in their physical activity and, especially, better maintain their post-intervention physical activity level. However, the results showed that cognitive training in addition to physical training did not have additive effects on physical activity over physical training alone. It is possible that the executive functions training program was too focused. It has been proposed that the effects of targeted cognitive training may not transfer to everyday life (Basak et al., 2020) and that improved performance in specific tasks may thus not relate to changes in more complex behaviors such as being physically active. Another explanation may be that the present intensive and long-term multidomain physical training intervention, requiring participants to monitor and plan their behavior, stimulated executive functions to such an extent that the additive benefits of targeted cognitive training were minor. This is supported by the previous finding that changes in other aspects of executive functions, i.e., task switching and working memory updating, did not differ between the study groups (Sipilä et al., 2021). Furthermore, the participants had a relatively high baseline level of general cognitive functioning and executive functioning. For example, the present participants performed slightly better in a test capturing global cognition and on a similar level in a test capturing inhibitory control compared to a sample of Finnish non-demented adults who were, on average, five years younger (Hooshmand et al., 2012). Thus, high baseline executive functions may have led to a ceiling effect and masked the potential benefits of executive functions training in addition to physical training for older adults with poorer executive functions.

Previous studies have shown that while physical activity interventions can lead to increased physical activity in older adults, these benefits tend to be short-lived (Sansano-Nadal et al., 2019). This was also found in the present study. While both accelerometer- and self-reported physical activity notably increased in both study groups from baseline to six months into the intervention, accelerometer-based light- and moderate-to-vigorous activity had returned to the baseline level at the twelve-month measurement. However, although self-reported physical activity attenuated somewhat after six months, it remained significantly above the baseline level. This is in line with findings from a recent meta-analysis showing a significant increase in self-reported physical activity at post-intervention in a general adult population, but a non-significant change in accelerometer-based physical activity (Howlett et al., 2019). One plausible reason for the discrepancy between the results of the measurements based on the different physical activity assessment tools in the present study is their timing. The participants filled in the physical activity questionnaire after their last supervised physical training session but before the twelve-month laboratory visit, and thus likely thought about the previous weeks when rating their current physical activity. In contrast, accelerometers were provided at the end of the twelve-month laboratory visit, and the assessment was thus performed immediately after the intensive year-long training program ended. The participants may have wanted a restorative break from exercising now that they were no longer bound to a structured training schedule. This highlights an important challenge related to accelerometers: they typically provide information on physical activity behavior over a limited period, the timing of which may markedly affect the results. Another possible explanation for the discrepancy between the results of the self-reported and accelerometer-based physical activity analyses is social desirability bias, i.e., participants may have wanted to present themselves in a positive light and thus selected a category higher than their baseline category in the post-intervention assessment.

Interestingly, most of the approximately half an hour per day increase in accelerometer-based physical activity from baseline to six months, was light-intensity activity, whereas the average daily increase in moderate-to-vigorous activity was only five minutes. In contrast, a shift from engaging in low-intensity activities only to also performing brisk activity was seen in the self-reported current physical activity category. This supports the earlier discussed view that the standardly defined accelerometer-based physical activity intensity categories probably underestimate activity intensity in older adults. As suggested by Kowalski and colleagues (2012), questionnaires are superior to accelerometry in assessing perceived and relative intensity of physical activity. That is, accelerometers capture the absolute intensity of the movement, whereas self-reports reflect the intensity perceived in relation to one's capacities. Therefore, it is likely that, in relation to the participants' perceived fitness level, moderate-intensity activity increased substantially during the study, despite the emphasis on light activity shown in the results from the accelerometry analyses.

Furthermore, this study showed that self-reported physical activity was higher than the baseline level at one-year follow-up and during the COVID-19 restrictions. Previous research on the long-term effects of physical activity interventions in older adults is scarce and has typically shown poor maintenance of physical activity (Sansano-Nadal et al., 2019), making these results encouraging. Interestingly, physical activity was even higher during the COVID-19 restrictions than at the one-year follow-up. These results are in accordance with those of a large British study showing increased physical activity among older adults during the COVID-19 pandemic (Strain et al., 2022), although most studies conducted among older adults have reported decreasing activity levels during this period (Christensen et al., 2022). In a previous study, being motivated and perceiving physical opportunities for physical activity were associated with physical activity during COVID-19 (Spence et al., 2021). Even though public sports facilities were closed in Finland during the restrictions, many private sports facilities remained open and there were opportunities for being active outdoors since no curfew was declared. The time of the restrictions – late spring and early summer – was an opportune time for, e.g., walking, yard work and gardening, which are popular types of physical activity among Finnish older adults (Wennman & Borodulin, 2021). Therefore, opportunities for being physically active were not as restricted in Finland as in many other countries. Furthermore, the fact that the present participants were used to home-based gymnastics and moderate-intensity outdoor activities during the intervention may have improved physical activity-related health literacy, which in turn may have helped motivate them to maintain a physically active lifestyle during exceptional circumstances. These findings indicate that a multicomponent physical training approach, which follows physical activity recommendations and includes both intensive supervised training and independent exercise, may facilitate sustained behavior change in previously physically inactive older adults.

Although the cognitive training did not provide additive benefits over physical training alone in this study, better baseline executive functions predicted higher physical activity in the subsequent measurements. These results support earlier research suggesting that executive functions may promote physical activity in older adults (Best et al., 2014; Daly et al., 2014; McAuley, Mullen, et al., 2011). The predictive effects of response inhibition, task switching and working memory updating varied slightly across the measurement time points, which mirrors the shared but also different characteristics of the three main facets of executive functions (Miyake et al., 2000). The Stroop test was the best predictor of future physical activity. The test capitalizes not only on inhibition but also on common executive functioning, that is, the capability to maintain and manage goals and, when necessary, to retrieve and update them (Friedman & Miyake, 2017). It is therefore reasonable that the Stroop test could capture the wide range of requirements that adopting and maintaining of a physically active lifestyle requires in varying circumstances.

Poor health is one of the major perceived barriers to physical activity among older adults (Rasinaho et al., 2007), and previous research has indicated that physical activity promotion interventions are somewhat less effective among multimorbid than healthy older adults (Chase, 2015). This may be explained by the tendency of people with chronic conditions to perceive high risks in engaging in physical activity, despite the fact that the benefits clearly outweigh the risks (Reid et al., 2021). Therefore, the results of this study showing that multimorbidity patterns had only a minor impact on the changes in physical activity and physical capacity during the year-long multicomponent physical training program are encouraging. These findings support and complement the results from a recent meta-analysis covering seven chronic conditions, which suggests that exercising is also safe and beneficial among multimorbid older adults (Bricca et al., 2020). Although the impacts of multimorbidity patterns on the changes in physical activity, aerobic endurance, muscle strength and power were very small, their impacts on the baseline level of physical activity and capacity were somewhat greater. Multimorbidity patterns explained, at the most, 12% of the variation in the baseline level of physical activity and capacity outcomes, and, at most, 3% of the variation in the amount of change in each outcome. While the effect sizes do not reveal the direction of the effect, investigation of the impact of individual chronic conditions showed a general negative trend at baseline. These findings are thus in line with previous research suggesting that multimorbid older adults are less physically active and have poorer physical capacity than their healthier counterparts (Keats et al., 2017; Ryan et al., 2015; Steeves et al., 2019). Overall, multimorbidity patterns did not have a negative impact on the training outcomes.

The present results also shed new light on the complexity of multimorbidity patterns and their impact on physical activity and physical capacity by investigating multimorbidity as a cluster of chronic conditions. Multimorbidity is most often defined as having two or more chronic conditions, with the number of included diseases and their risk factors varying across definitions (Johnston et al., 2019; Willadsen et al., 2016). This study showed that different chronic conditions varied in their impact on the different physical activity and physical capacity outcomes, a result that would have remained unnoticed had the traditional approach of dichotomizing multimorbidity status into either being or not being multimorbid been applied. The results also showed that the impact of multimorbidity patterns varied across the time points and between men and women, but the impact of most chronic conditions was non-significant and/or was inconsistent across the outcomes and time points. Some conditions even had a positive impact on the baseline level of or change in some outcomes. Thus far, while no physical activity recommendations for multimorbid people exist (Muth et al., 2019), the present findings indicate that multimorbid older adults can benefit to similar extent as healthier peers from multicomponent exercise following the general physical activity recommendations for older adults.

6.4 Ethical considerations

It is of special importance when performing clinical trials among vulnerable populations, e.g., older adults, that ethical principles are followed. Therefore, ethicality and responsibility were key principles throughout this study. Recruitment to the study was carefully planned and implemented to minimize any potential measurement- and/or training-related risks to individual participants, i.e., older adults whose physical, cognitive, or mental health could have compromised their safety or understanding of commitment they would be making to the study were excluded. Participants had already been informed about the potential harms and risks related to participation, e.g., the dose of radiation in the DXA measurement, in the initial recruitment letter. The research staff participating in the data collection and implementing the intervention were trained in safety and privacy issues. If cause for concern arose during the laboratory visits, e.g., during the cognitive functioning tests or in blood samples, or during the training sessions, the participants concerned were guided to further examinations in the healthcare services.

The intervention was carefully planned to minimize training-related risks and harms. The physical training program was planned in accordance with the physical activity guidelines for older adults. Training specificity, intensity and volume varied during the intervention year to avoid overtraining and fatigue. Exercises were individually tailored in case of injuries or illnesses in concert between the project investigator, study nurse, physician, and supervisors. Adverse events were carefully tracked and reported by Sipilä et al. (2021). First aid was provided on-site if necessary, and participants had a possibility to visit the study nurse and/or physician if needed. It was important for the cognitive training component that the supervisors had studied psychology, as the program was challenging and potentially frustrating. Therefore, the capability to provide support at moments of disappointment was crucial. To allow for adaptation to the intervention and to avoid excess training-related fatigue, cognitive training was initiated for each participant approximately two months after the beginning of the physical training program.

6.5 Methodological considerations

This dissertation research drew on data gathered for a larger RCT, the PASSWORD study. These data offered an excellent opportunity to explore physical activity in community-dwelling older adults from different perspectives. The PASSWORD study comprised 314 men and women aged from 70 to 85 year and resident in Jyväskylä, Finland who were physically inactive yet relatively healthy and well-functioning and willing to engage in a year-long intensive physical training program with or without a cognitive component. A strength of this study was the use of a relatively large random population-based sample. However, the target population challenges the generalizability of the results from the present study in various ways. First, this study does not provide knowledge on physical activity and its associations with body composition and physical capacity in highly active older adults. Therefore, conclusions cannot be drawn on the associations of high-intensity physical activity or impacts with body composition and physical capacity. Furthermore, older adults with cognitive decline, mobility disability, and more severe conditions were excluded. Hence, the impacts of more severe multimorbidity patterns on physical activity or physical capacity could not be investigated, and no conclusions can be drawn on whether older adults with impaired physical or cognitive functioning would benefit more from combined physical and cognitive training than from physical training alone.

Despite its limitations, the target study population of physically inactive yet relatively well-functioning older adults was close to optimal from a health promotion perspective. Screening was relatively successful, since only 13% of the participants reported engaging in brisk physical activity or keep-fit exercise three or more times per week at baseline, and the median volume of moderate-to-vigorous activity in bouts of at least ten minutes was around one hour per week, as reported by Sipilä et al. (2021). Furthermore, regular participation in muscle strengthening activities was an exclusion criterion, i.e., participants did not meet the recommendations for weekly muscle strengthening activity. The participants were thus less physically active than recommended at the time of the study and could be expected to benefit notably from increasing their amount of physical activity. Since they did not have contraindications for engaging in exercise, they could undertake an intensive physical training program with potential benefits for health and functioning. It should, however, be noted that the participants were found on average to have recorded half an hour per day of moderate activity when activity bouts of any intensity were calculated, a dose which meets the current revised recommendations for aerobic activity. Furthermore, if age- or fitness-adjusted physical activity intensity cut-offs had been applied, the total volume of moderate-to-vigorous intensity activity would presumably have been even higher. This reflects the difficulty of recruiting sedentary but relatively well functioning and healthy older adults willing to engage in a year-long exercise program.

One of the major strengths of the present study is the exploration of physical activity with several different measures, including both self-reported and device-based physical activity outcomes. In addition to the traditional approach to processing raw accelerometer data, based on intensity categories, physical activity outcomes also included impact-based outcomes and physical activity intensity distribution along the whole intensity range. These approaches yielded novel information on older adults' physical activity. For example, the results reported in Sub-study I showed that the relationship of physical activity with lower body fat and faster walking speed became significantly positive already within the sedentary behavior intensity range. On the other hand, investigating the associations at the higher end of the intensity range was not feasible. Activity intensities exceeding 3.1 g, corresponding to walking at approximately 5 km/h, were excluded from the analysis, since less than one third of the participants recorded any activity exceeding this intensity.

One strength of the present study was the high compliance with the accelerometer-wear instructions, resulting in on average 6.7 wear days and 14 hours of wear-time per day in the baseline measurements. Only three participants were excluded from the baseline accelerometry analyses due to insufficient use. Unfortunately, technical failures led to missing accelerometry data at the baseline from 18 participants, thus restricting the sample size for all analyses on accelerometer-based physical activity. One obvious limitation of the accelerometer-based physical activity assessment in the present study was the non-optimal timing of the twelve-month measurement. Participants received the accelerometers according to similar procedure as followed at the baseline and six-month measurements, i.e., at the end of the twelve-month laboratory visit. At that time, the intensive year-long physical training program had just ended, and participants may have felt fatigued and in need of a rest. This was noticed in the post-intervention interviews conducted with the participants as part of the twelve-month laboratory visit, when they were encouraged to continue exercising and received information on the opportunities provided for older adults by the City of Jyväskylä. Many participants said that they aimed to "take some time off from exercising" and look at these opportunities later. To form a more reliable picture of the intervention effects on physical activity at the end of the intervention and on the maintenance of physical activity thereafter, it would have been better to have collected the twelve-month data during the last intervention week and then conduct a short-term follow-up assessment, for example, one month later. This was the main reason for choosing self-reported physical activity as the outcome in Sub-study III and not including accelerometer-based outcomes in Sub-study IV.

Due to the limitations in the accelerometer-based physical activity measurements, it was important that physical activity was also assessed by a questionnaire. Questionnaires enable data to be collected from large study samples quickly and at relatively low cost (Strath et al., 2013). In the present study, questionnaires enabled tracking the maintenance of physical activity after the intervention and conducting an extended follow-up during the COVID-19 restrictions. Although it has been suggested that questionnaires are not as sensitive as accelerometers in detecting intervention-related change in physical activity (Nigg et al., 2020), this study showed statistically significant changes in self-reported physical activity over the study period. However, the one-item global questionnaire may not have been sensitive enough to detect differences in physical activity between the two study groups. An additional limitation of the questionnaire was its inability to assess, e.g., low-intensity incidental activity. These are better captured with accelerometers than questionnaires (Ainsworth et al., 2015; Strath et al., 2013). Therefore, it would have been valuable to have repeated the accelerometer-based physical activity measurements at the one-year follow-up and during the COVID-19 restrictions to gain a more comprehensive view of the maintenance of physical activity. Unfortunately, this was not possible due to limitations on resources. Furthermore, none of the physical activity assessment methods in the study were able to assess adherence to the physical activity recommendations. Moreover, none of the assessment tools accurately captured the muscle-strengthening and balance-enhancing components of the physical activity recommendations. Utilizing a physical activity diary or a more complex questionnaire with more items covering the frequency and types of participants' habitual physical activity levels across the intensity spectrum, would have complemented the single-item questionnaire and accelerometry.

Utilizing data from a large-scale research project also provided an opportunity to study the relationship of physical activity with different aspects of health and functioning. The main aim of the PASSWORD study was to investigate the additive effects of physical and cognitive training on walking speed, executive functions, and falls. compared to physical training alone. Therefore, executive functions and physical functioning were carefully mapped during the study with diverse validated tests assessing different facets of executive functions, physical capacity, and body composition, all of which are important determinants of cognitive and physical functioning. However, some of these measurements also have their limitations. The SPPB test, which was an exploratory outcome, is commonly used to assess lower extremity functioning and potential mobility limitations; however, it is limited in its capability to differentiate and detect improvements in lower extremity functioning in well-functioning older adults (Puthoff, 2008). Therefore, only the sub-component five-time chair stand time, which showed on average the lowest baseline score of the three components, was utilized in Sub-study III. It seemed plausible that this component would have most room for improvement. DXA provides a single imaging tool to assess both fat, lean, and bone mass accurately (Shepherd et al., 2017). However, DXA does not provide a precise estimate of skeletal muscle mass, since the lean mass outcome also includes other tissues such as skin, and it is less precise in assessing bone mass in older than in younger adults (Laskey, 1996; Müller et al., 2014). Use of other imaging techniques would probably have provided more accurate estimates of muscle mass and bone strength than DXA. However, appendicular lean mass is suggested to be a reliable estimate of skeletal muscle (J. Kim et al., 2002) and was thus chosen as an outcome instead of total body lean mass. Furthermore, we extended the conventional DXA-based analyses on bone mineral content and density and included outcomes describing the bending strength and structure of the femoral neck, i.e., section modulus and minimal neck width, from the hip structural analysis (Beck, 2007).

The research questions set for this dissertation were answered using both cross-sectional and longitudinal study designs. Due to the cross-sectional nature of Sub-studies I and II, causal relationships between physical activity and impact intensities with body composition and physical capacity could not be explored. The intervention effects, reported in Sub-studies III and IV, were exploratory, as the analyses were based on outcomes and approaches that were not pre-registered as primary or secondary analyses of the PASSWORD study (Sipilä et al., 2018). Therefore, the outcome measures and sample sizes of these sub-studies were not optimized for addressing the research questions. However, the RCT design in Sub-study IV enabled investigation of the additive effects of cognitive training, as an adjunct to physical training, on physical activity compared to physical training alone for the first time. Another unique strength of this research was the investigation of the long-term maintenance of physical activity during exceptional circumstances, i.e., when many people's physical activity routines were disrupted by the COVID-19 restrictions. While changes in physical activity on the population level during the pandemic have been widely studied, most of this research has been cross-sectional and has included very few population-based longitudinal studies (Christensen et al., 2022; Strain et al., 2022). This study is the first to investigate physical activity maintenance during the COVID-19 restrictions after a physical training intervention and thus makes a valuable contribution to the literature by showing that older adults who were used to regular exercising were able to maintain and even increase their physical activity levels during this exceptional period. However, the RCT design was limited as it did not include a non-training or cognitive training only control group. Future trials with a non-training control group or other type of physical activity promotion intervention are thus required to verify the effectiveness of the present multicomponent physical training program in increasing physical activity among physically inactive community-dwelling older adults.

A clear strength of the present study is the high retention rate. Only 7% of the participants dropped out of the PASSWORD study during the intervention year, and 88% of the participants initially recruited responded to the extended follow-up questionnaire during COVID-19. Some differences in socio-demographic and health-related characteristics were observed between dropouts and remainers at different phases in the study. The attrition analyses indicated that dropouts were slightly older, less fit, and less physically active at baseline than those who remained in the study throughout the intervention and follow-up. Hence, it is possible that the results showing an increase in physical activity are somewhat optimistic.

The GEE method was chosen for the longitudinal analyses reported in Sub-study III and for the unpublished analyses on changes in accelerometer-based physical activity owing to its ability to deal with missing data. Thus, it was not necessary to exclude from the analyses participants with missing physical activity data on one or more of the follow-up measurements or perform imputations. A further benefit of the method is that it is flexible with respect to the distribution of outcomes and accounts for within-subject correlations between measurements. Since the results on the effects of the intervention on physical activity from baseline to 12 months were different for self-reported and accelerometer-based physical activity, the study would have benefited from complementary longitudinal analyses investigating the correlation between self-reported and accelerometer-based physical activity outcomes over time. In Sub-study III, we report a novel analysis strategy in which we investigated the impact of multimorbidity on physical activity and capacity by including all chronic conditions and BMI in the GEE model instead of categorizing the multimorbidity outcome. Thereafter, Wald tests were calculated to reveal the total effect size of the cluster of chronic conditions on the physical activity and physical capacity outcomes over time. This approach provided not only new knowledge on the impact of multimorbidity patterns on the intervention effects but also insights on the impacts of individual conditions. Hence, the results showed that while, as expected, some conditions had a negative impact, others had no significant impact or even a positive impact on the effects of the intervention. Although these findings shed new light on the role of multimorbidity patterns on physical activity and capacity, some of the conditions were rare and hence the levels of statistical significance of the impacts of individual conditions need to be interpreted with caution. Furthermore, the heterogeneity of the multimorbidity patterns was wide in relation to the sample size, and thus prohibits the drawing of firm conclusions on the impact of different multimorbidity patterns on physical activity and physical capacity.

6.6 Future directions

This study contributes to the literature on older adults' physical activity. The results provide novel insights on physical activity accumulation along the whole intensity range. The majority of daily activity was accumulated at very low intensities, whereas the volume of high-intensity activity, expressed in both minutes and impacts, was minimal. This research strengthened the existing evidence on the positive relationship between physical activity, body composition and physical capacity, and yielded novel knowledge on the positive nature of the relationship between even very light-intensity physical activity with lower body fat and faster walking speed. This study is one of the first to investigate impact-based physical activity in older adults. The results showed – against expectations – that light-intensity, but not impact-based measures of physical activity were positively associated with proximal femur bone traits. Future studies are required in more diverse populations to map the accumulation of physical activity and to investigate the relationships of physical activity and impact intensities with health-related outcomes in both frailer and highly active older adults. In addition, to accurately assess older adults' bone strength and structure and describe the relationships between physical activity and bone health in older age, it would be important to include imaging techniques more suitable for these purposes. Furthermore, to investigate the causal relationships of physical activity and impact intensities with body composition and physical capacity outcomes requires studies utilizing longitudinal and intervention designs.

Based on the findings of the present study, future research should also target the development of accelerometer-data processing and analytical methods suitable for older adults. The results of this dissertation research indicate that the cut-offs for light-, moderate- and vigorous-intensity activity need to be validated separately in older adults. While it is plausible that the cut-offs validated among younger people are too high for most older adults, this remains an educated guess without validation studies conducted among older adults with varying fitness levels. Furthermore, older adults are a very heterogenous group, varying widely in physical activity and fitness level. Developing procedures to define individualized physical activity intensity is thus required.

The results of this dissertation research did not support the hypothesis that targeted executive functions training may have additive effects over physical training alone on increasing physical activity. However, the results showed that executive functions may support the adoption and maintenance of physical activity. These findings warrant future research on whether complementing physical training with another type of executive functions training would promote physical activity better than physical training alone. For example, it has been proposed that cognitive control training facilitating mind-body connection or targeting cognitive processes required for being physically active could be more effective in increasing physical activity than a computerized cognitive training program comprising focused tasks such as that used in the present study (Buckley et al., 2014). Furthermore, it would be important to investigate whether gradual reduction in supervised exercise and more support for self-motivated exercise would better facilitate the maintenance of physical activity after the end of the structured and supervised intervention period. To provide a more comprehensive understanding on physical activity change and maintenance, follow-up data on physical activity should also be collected by accelerometers as an adjunct to questionnaires. More detailed physical activity questionnaires and diaries could also be used to reveal engagement in different types of physical activity. Moreover, to overcome the limitations related to the timing of accelerometry, more long-term accelerometry data would need to be collected.

This study extends the literature on the impact of multimorbidity patterns on physical activity and physical capacity among older adults participating in a structured physical training program. However, due to the heterogeneity of the participants' chronic conditions and their combinations, it was not possible to reliably assess the impact of rarer conditions or specific combinations of conditions on physical activity and capacity. Therefore, more research in larger or more focused study samples is required to broaden our understanding of the impact of different multimorbidity patterns on physical activity and physical capacity. Research aiming at the inclusion of physical activity recommendations in the clinical guidelines for treating multimorbidity is also essential.

7 MAIN FINDINGS AND CONCLUSIONS

The main findings and conclusions of the present study can be summarized as follows:

1. Older adults who reported being physically inactive accumulated most of their daily physical activity at very light intensities. The volume of activity at the higher end of the intensity range and counts of high-intensity impacts were small.

2. Self-reported physical activity showed mostly weak correlations with accelerometer-based outcomes, whereas the strength of the associations between intensity- and impact-based outcomes varied widely. Self-reported and different accelerometer-based methods complement each other in physical activity research among older adults.

3. Physical activity of any intensity, even below the cut-off for light activity, was associated with lower fat percent, better aerobic endurance, and faster walking speed, but only activity at the higher end of the intensity range was associated with lower extremity functioning. Only light physical activity had a consistent positive association with bone traits. A large amount of light-intensity ambulatory activity may, when the volume of high-intensity impact activity is low, prevent excess fat gain and bone loss and promote walking ability.

4. Physical and cognitive training did not provide additive effects over physical training alone on increasing physical activity, although better baseline executive functions predicted higher future physical activity. Other types of executive functions training may be required to facilitate increased physical activity.

5. The year-long multicomponent physical training intervention with or without cognitive training led to a sustained increase in self-reported

physical activity during the intervention, after one-year follow-up and during the COVID-19 restrictions. The increases in accelerometer-based physical activity observed from baseline at six months into the intervention had diminished at twelve months, highlighting the importance of measurement timing and a potential decline in physical activity immediately after an intensive intervention.

6. Multimorbidity patterns had a very small and thus probably not clinically meaningful impact on changes in physical activity and physical capacity during the year-long multicomponent intervention. While the magnitude and direction of the impact varied across the chronic conditions and outcomes, most conditions had no significant impact. Older adults with multimorbidity may benefit from multimodal physical training.

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ORIGINAL PAPERS

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ASSOCIATIONS OF PHYSICAL ACTIVITY IN DETAILED INTENSITY RANGES WITH BODY COMPOSITION AND PHYSICAL FUNCTION. A CROSS-SECTIONAL STUDY AMONG SEDENTARY OLDER ADULTS

by

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RESEARCH ARTICLE Open Access

Associations of physical activity in detailed intensity ranges with body composition and physical function. a cross-sectional study among sedentary older adults

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Abstract

Background: Physical activity is crucial to maintain older adults' health and functioning, but the health benefits of particular activity intensities remain unclear. The aim of this cross-sectional study was to peruse the distribution of physical activity, and to investigate the associations of particular physical activity intensities with body composition and physical function among older adults.

Methods: The sample comprised of 293 community-dwelling sedentary or at most moderately active older adults (42% men, mean age 74 ± 4 years). Physical activity was measured with a hip-worn tri-axial accelerometer over seven consecutive days, and investigated in detailed intensity range and in categories of sedentary, light and moderate-to-vigorous activity. Fat percent and appendicular lean mass were measured with DXA. Physical function was assessed by six-minutes walking test (6-min walk), maximal walking speed over 10 m (10-m walk) and Short Physical Performance Battery (SPPB). Associations were estimated with partial correlation adjusted for sex and age.

Results: Participants spent on average 602 min per day sedentary, 210 min in light activity and 32 min in moderate-to-vigorous activity. Light and moderate-to-vigorous activity were negatively associated with fat percent ($r = -0.360$ and $r = -0.384$, respectively, $p < 0.001$ for both), and positively with SPPB, 10-m walk and 6-min walk results ($r = 0.145$–0.279, $p < 0.01$, for light and $r = 0.220$–0.465, $p < 0.001$, for moderate-to-vigorous activity). In detailed investigation of the intensity range, associations of physical activity with fat percent, 6-min walk and 10-m walk were statistically significant from very light intensity activity onward, whereas significant associations between physical activity and SPPB were observed mostly at higher end of the intensity range. Sedentary time was positively associated with fat percent ($r = 0.251$, $p < 0.001$) and negatively with 6-min walk ($r = -0.170$, $p < 0.01$).

Conclusion: Perusing the physical activity intensity range revealed that, among community-dwelling sedentary or at most moderately active older adults, physical activity of any intensity was positively associated with lower fat percent and higher walking speed over long and short distances. These findings provide additional evidence of the importance of encouraging older adults to engage in physical activity of any intensity. More intervention studies are required to confirm the health benefits of light-intensity activity.

Keywords: Accelerometer, Physical performance, Walking speed, Fat percent, Community-dwelling

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Background

Promoting physical activity and health of older adults is crucial. Deterioration of physiological functions and body composition together with declines in physical activity by aging are associated with deterioration of physical function [1] and loss of mobility [2]. Physical activity is known to counteract many of the unfavorable age-related changes in health and functioning [3]. For example, physical activity contributes to maintenance of healthy weight, cardiovascular health, muscular strength and physical functioning [3, 4]. In contrast, sedentary behavior has emerged as an independent risk factor for poor health and mortality [5], and has been associated with e.g., obesity [5], muscle weakness [6] and mobility disability [7] among older adults.

The health benefits of moderate-to-vigorous intensity activity for older adults are well-known [1, 4]. Participation in regular exercising maintains physical function [8]. Recent cross-sectional studies have consistently shown a positive association between habitual accelerometer-measured moderate-to-vigorous-intensity activity and better performance in physical function tests including endurance, strength and agility [9–14]. Higher levels of overall accelerometer-based physical activity and moderate-to-vigorous-intensity activity in particular may also help to maintain muscle mass in old age [15], but this is not supported by all studies [14]. A growing body of evidence indicates that even light-intensity activity may lower mortality risk [16, 17] and the risk of obesity [16], delay brain aging [18], and provide other health benefits for older adults [16]. Preliminary evidence from a cross-sectional study indicates that habitual accelerometer-based light-intensity activity may be beneficially associated also with physical function among older adults [10], but the data are still few and inconsistent. Other recent studies have shown no association between light physical activity and physical function [9, 11], or the association has not been significant throughout the spectrum of light-intensity activity or in both sexes [13]. Even though physical activity is known to maintain healthy weight, muscle strength and physical functioning in older age [3, 4], the associations of particular physical activity intensities with physical function and body composition remain unclear among older adults.

Despite the benefits of physically active lifestyle, many older people spend most of their awake time sedentary [19] and have difficulties to achieve or maintain moderate-to-vigorous-intensity activities in longer bouts [20]. In contrast, older adults often engage in lighter-intensity activities, such as casual walking or household activities [20]. For many sedentary older adults these activities may be significantly more strenuous than for young and fit individuals [4, 21], and the standardly defined cut-points for accelerometer-based moderate-intensity activity may thus underestimate the intensity of habitual physical activity among older adults [22]. Perusing accelerometer data in more detailed than in simple metrics, such as mean daily minutes in intensity categories or step counts, is therefore essential to widen our understanding of what physical activity metrics are significant for older adults' health and functioning [23].

The purpose of this cross-sectional study was to describe the distribution of accelerometer-measured habitual daily physical activity in detailed intensity range utilizing a novel analysis approach, and in categories of sedentary, light and moderate-to-vigorous-intensity activity, and to investigate what intensities were associated with measures of body composition and physical function in a representative sample of community-dwelling, sedentary or at most moderately active 70–85 year old men and women.

Materials and methods

Study design and participants

This cross-sectional study utilized the baseline data of the PASSWORD -study. Recruitment process and measurements have been described in detail by Sipilä et al. [24]. To be included, participants had to be 70–85 year old, community-dwelling, able to walk 500 m without assistance, to be sedentary or at most moderately active (less than 150 min of walking/week and no attendance in resistance training) and to score ≥ 24 points in Mini Mental State Examination test (MMSE). Exclusion criteria were: severe chronic condition or medication; other medical, psychiatric, or behavioral factor that may interfere with study participation; excessive alcohol use; severe vision or hearing problem; other family member participating in the XX -study. In total, 314 men and women were recruited of which 293 had acceptable accelerometer data. Flow chart is shown in Fig. 1.

Measurements

Physical activity

Tri-axial accelerometer, model UKK RM42 (UKK, Tampere, Finland) was used. Participants were instructed to wear the accelerometer seven consecutive days in an elastic waistband above the iliac crest on the right side during waking hours, except during water-based activities. Participants kept a diary of wearing hours as well as times and reasons for taking off the accelerometer for more than 30 min. Days with at least 10 h of wear-time were considered acceptable and data from participants with at least 3 acceptable days were included in the present report.

The UKK RM42-accelerometer measures and stores acceleration at 100 Hz sampling rate with 13-bit A/D conversion of the ±16 g range. Activity and inactivity thresholds of the devices were adjusted to account for the slower pace of movement of older adults. The recorded raw acceleration data were analyzed off-line with a custom-written MATLAB (version R2016b, The MathWorks Inc., Natick MA, USA) script. The Euclidian norm

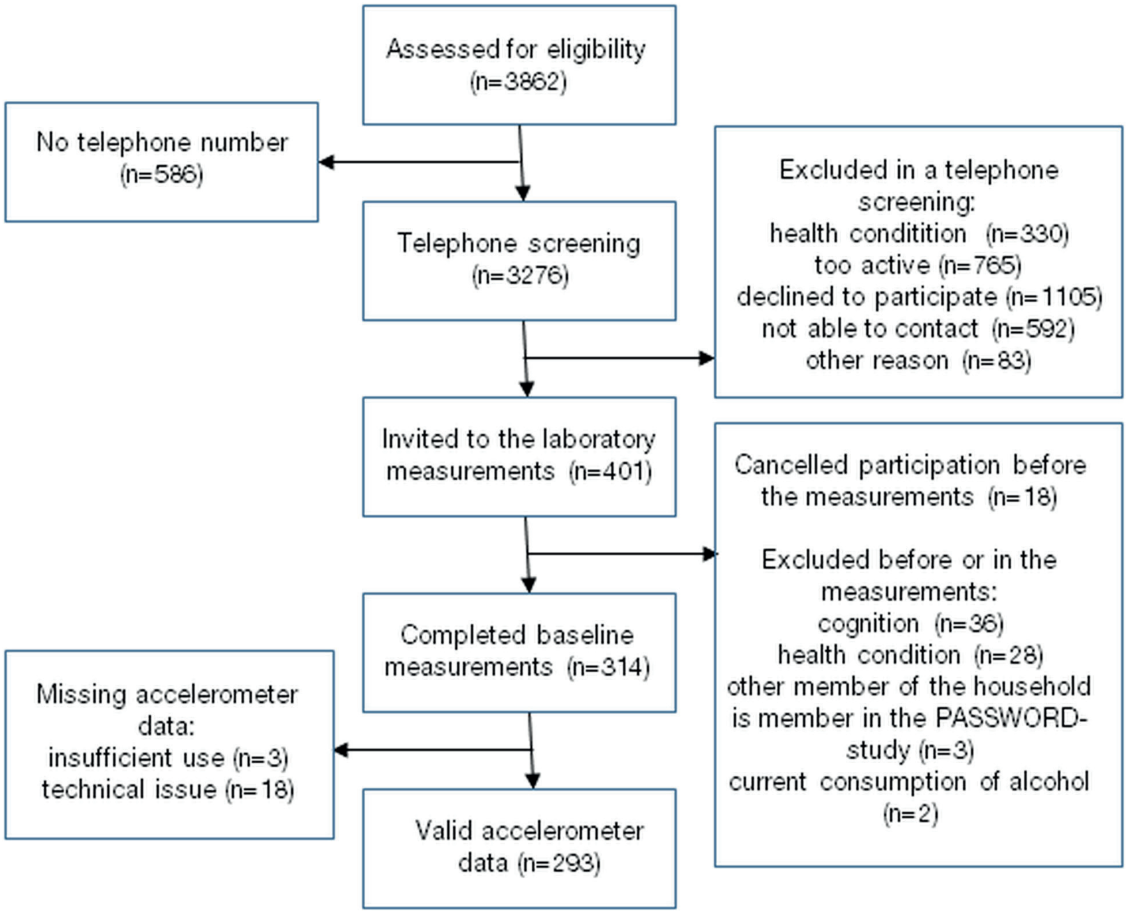

Fig. 1 Flow chart of the study

(resultant) of each acceleration sample was calculated, and further analysis was based on the resultant acceleration. The resultant was analyzed in five-second (5-s) non-overlapping epochs for mean amplitude deviation (MAD) [25]. That is, the mean of a given 5-s epoch was calculated and subtracted from the resultant accelerations, the absolute (negative signs were changed to positive) was taken from each value, and the mean of the absolute values was used as the 5-s MAD for the epoch. The epochs were divided into 24-h segments based on the diaries, and the mean of non-overlapping 1-min 5-s MAD epochs was calculated from mid-night to mid-night. Non-wear time was subsequently taken off as any epoch of at least 60-min with the 1-min MAD values continuously below 0.02 g. The non-wear algorithm resulted in good correspondence to the participant-reported diary-based wear-time.

The mean daily amount of physical activity was divided into two histograms based on the 1-min epochs. The first was based on the de facto standard of dividing the day into sedentary (bin threshold < 0.0167 g), light (≥ 0.0167 to < 0.091 g), moderate (≥ 0.091 to < 0.414 g), and vigorous (≥ 0.414 g) activities. Due to the very limited amount of vigorous-intensity activity, moderate and vigorous intensity activities were combined. The cut-points have been defined and validated against VO_2 [25, 26], and compared with widely used Freedson's cut-points for activity counts from uniaxial ActiGraph GT3X [27] in healthy younger adults, but not in older adults. In the last-mentioned study, MAD values showed slightly more sedentary activity, but notably less light activity and more moderate activity than activity counts. The amount of vigorous activity was similar [27]. To investigate the physical activity intensity range in detail, a second histogram with histogram bins from zero to 1.2 g in base 10 logarithmically equidistant bins was calculated [28], which resulted in 93 bins with at least some activity recorded. The use of logarithmically equidistant bins allows for a more detailed investigation of lower intensity activities, i.e. the bins are narrower at the lower intensities and wider at the higher intensities.

Body composition
Dual-energy x-ray absorptiometry (DXA, LUNAR Prodigy, GE Healthcare) was used to measure fat percent and appendicular lean mass. Participants were scanned in supine position in the center of the table using the default-scanning mode for total body automatically selected by the Prodigy software (Lunar Prodigy Advance Encore v. 14.10.022).

Physical function
Physical function measures included six-minutes walking distance (6-min walk) [29], maximal walking speed (m/s) over 10 m (10-m walk) [30] and Short Physical Performance Battery (SPPB) [31]. In 6-min walk participants walked a 20-m track back and forth in a comfortable pace without resting for 6 min, and total distance walked was recorded in meters. In 10-m walk, participants were asked to walk over the 10 m course as fast as possible without compromising safety. The fastest time of two trials was accepted as the result, and maximal walking speed was calculated (m/s). The SPPB assesses lower extremity functioning and includes habitual walking speed over four meters, five-time chair rise time and standing balance tests. The score varies between 0 and 12 and the higher score indicates better performance [31].

Background characteristics
Sex and date of birth were drawn from the population register. Anthropometrics were measured using standard procedures. Other background characteristics were drawn from a comprehensive questionnaire, and included highest education (low, i.e. primary school or less, medium, i.e. middle school, folk high school, vocational school or secondary school, vs. high, i.e. high school diploma or university degree), current self-perceived health (very good/good vs. average/poor), and current self-perceived mobility (very good/good vs. poor/very poor).

Statistical analyses
Descriptive data are expressed as means and standard deviations (SD) for continuous variables and frequency (n) and percentage (%) for categorical variables in all participants and for men and women separately. To illustrate the distribution of physical activity along the whole intensity range, the mean minutes per day and number of participants having any recorded activity at each of the logarithmically equidistant intervals are presented as diagrams.

The associations of the mean daily minutes in sedentary, light and moderate-to-vigorous-intensity activity, with the body composition and physical function measures were assessed with partial correlation (Pearson) adjusted for sex and age. The associations of light-intensity activity with body composition and physical function indicators were further controlled for time spent in moderate-to-vigorous-intensity activity and vice versa. To investigate the strength of the associations along the whole physical activity intensity range, partial correlation coefficients were calculated for time spent at each of the logarithmically equidistant intervals and each body composition and physical function variable. Results are presented in graphs as correlation coefficient r and 95% confidence interval (CI). Graphs present correlations for activity intensities from 0.00188 g to 0.31 g since the first bin included the non-wear time and the amount of data on intensities exceeding 0.31 g was very limited. Statistical analyses were performed with IBM SPSS Statistics 24 (SPSS Inc., Armonk, NY). Statistical significance level was set at 0.05 for all analyses.

Results
Participant characteristics
Descriptive data are presented in Table 1. Mean age was 74 years, and 28 participants were ≥ 80. The average fat percent was 19% and participants had on average 36 kg of appendicular lean mass. In 6-min walk the mean distance completed was 478 m. The mean score in SPPB was 10 and the average speed in 10-m walk was 2 m/s.

Participants wore the accelerometer on average 14 h per day and had on average 6.7 acceptable measurement days. Participants spent on average 602 min, i.e. 10 hours, per day sedentary. Light-intensity activity covered on average 210 min (3.5 h) and moderate-to-vigorous-intensity activity 32 min (0.5 h) of mean daily wear-time (Table 1). Most of the active time was spent in very light-intensity activity with a drastic decrease from 19.4 min in the first to 1.7 min in the last bin within the light-intensity range (Fig. 2a). Within the moderate-intensity range, most time was spent at the lower intensities, the mean time spent at each of the intervals decreased gradually, and the amount of vigorous-intensity activity (≥ 0.414 g) was nearly non-existing. All participants had at least some moderate-intensity activity (≥ 0.091 to < 0.414 g) (Fig. 2b). A steep decline was observed in the number of participants having some activity exceeding 0.16 g. Less than one third of participants reached accelerations exceeding 0.31 g, and only few had any vigorous-intensity activity.

Associations of accelerometer-measured physical activity with body composition and physical function
Time spent in sedentary activity was positively associated with fat percent and negatively associated with 6-min walk (Table 2). Time spent in both light and moderate-to-vigorous-intensity activities was negatively associated with fat percent and positively associated with 6-min walk, 10-m walk and SPPB. Appendicular lean

Table 1 Descriptive statistics in full sample and according to sex (mean ± standard deviation or frequency (%))

	All (n = 293)	Men (n = 122)	Women (n = 171)
Age, years	74.44 ± 3.78	74.35 ± 3.90	74.50 ± 3.69
Anthropometrics			
Height, m	1.66 ± 0.09	1.73 ± 0.06	1.61 ± 0.06
Weight, kg	76.84 ± 14.35	84.07 ± 12.45	71.68 ± 13.39
Body mass index, kg/m^2	27.88 ± 4.77	27.88 ± 3.60	27.87 ± 5.46
Waist circumference, cm	95.69 ± 12.47	102.11 ± 9.73	91.11 ± 12.20
Basic education, n (%)			
Low	43 (15)	25 (21)	18 (11)
Medium	186 (64)	77 (63)	109 (64)
High	64 (22)	20 (16)	44 (26)
Current self-rated health, n (%)			
very good/good	135 (46)	55 (45)	80 (47)
average/poor	158 (54)	67 (55)	91 (53)
Current self-rated mobility, n (%)			
very good/good	269 (92)	113 (93)	155 (91)
poor/very poor	25 (9)	9 (7)	16 (9)
Body composition[a]			
Fat percent	35.94 ± 8.23[a]	30.15 ± 6.01[a]	40.04 ± 7.04
Appendicular lean mass, kg	19.40 ± 4.37[a]	23.69 ± 2.95[a]	16.36 ± 2.05
Physical function			
6-min walk, m	477.55 ± 82.56	502.60 ± 90.68	459.68 ± 71.30
10-m walk, m/s	1.98 ± 0.38	2.11 ± 0.45	1.88 ± 0.29
SPPB, total score	10.19 ± 1.54	10.64 ± 1.45	9.87 ± 1.53
Accelerometer-measured physical activity			
Valid days	6.7 ± 0.8	6.7 ± 0.7	6.6 ± 0.8
Wear time, h/d	14.1 ± 1.3	14.3 ± 1.3	13.9 ± 1.2
Sedentary activity, min/d	602.3 ± 82.9	627.1 ± 81.0	584.6 ± 79.9
Light activity, min/d	210.3 ± 66.3	196.9 ± 60.8	219.8 ± 68.6
Moderate-to-vigorous activity, min/d	32.5 ± 20.1	33.1 ± 21.0	32.1 ± 19.5

Note
Abbreviations: 6-min walk = distance walked in 6 mins; 10-m walk = maximal walking speed over 10 m; *SPPB* Short Physical Performance Battery
[a]Missing n = 1

mass was not associated with any physical activity intensity category (Table 2). Adjusting the associations of light activity with body composition and physical function for time spent in moderate-to-vigorous activity and vice versa did not notably change the results except that the association between light activity and SPPB was no longer significant.

When the associations were investigated in detailed intensity ranges, a statistically significant negative association was found between fat percent and mean daily minutes in each of the logarithmically equidistant bins apart from few exceptions, which did not reach statistical significance. Magnitudes of the associations are given in Fig. 3a. For appendicular lean mass, a statistically significant positive association was only found for few narrow intensity ranges at the lower end of moderate-intensity range (Fig. 3b). All activity intensities were positively associated with 6-min walk (Fig. 4a). Associations between 10-m walk and physical activity were statistically significant along almost whole physical activity intensity range (Fig. 4b). SPPB had a significant positive association with physical activity in the higher end of the examined intensity range and in few intensities within the light-intensity range (Fig. 4c).

Discussion

We found that community-dwelling older adults, who reported to be sedentary or at most moderately physically active, spent most of their waking hours sedentary and in very light-intensity activities. Both light and moderate-to-vigorous activity were associated with lower

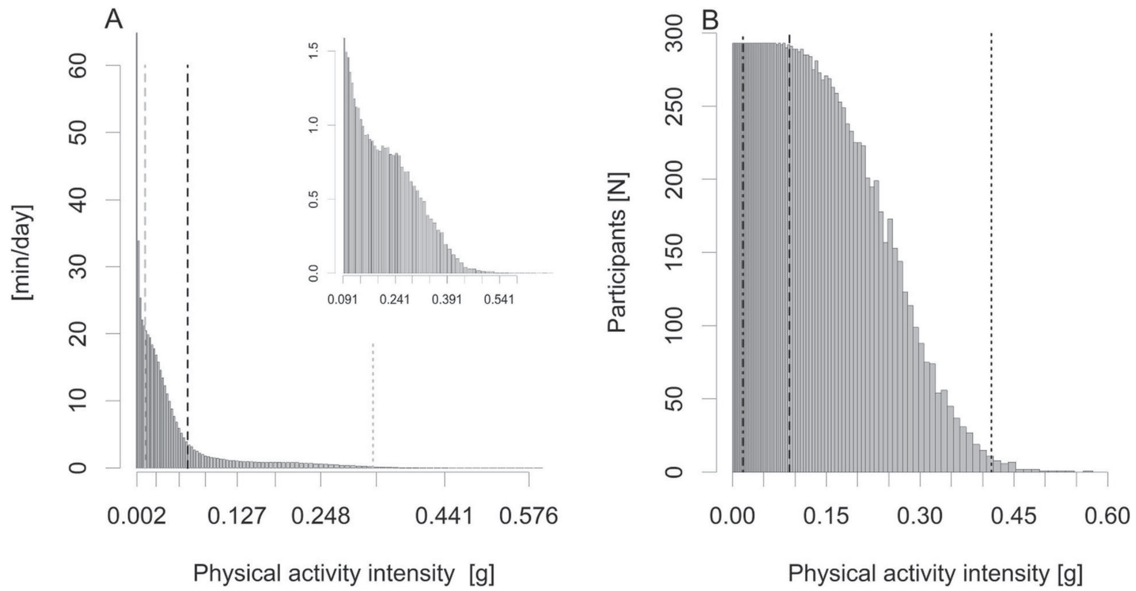

Fig. 2 Distribution of physical activity in detailed intensity range. **a** for mean daily minutes (y-axis) at each of the logarithmically equidistant intervals along the whole intensity range (x-axis) from sedentary to vigorous intensity activity (0.00188 g to 0.62305 g), and within moderate-to-vigorous-intensity activity range (**a**, imputed small figure). **b** for number of participants (y-axis) having some activity at each interval (x-axis). The verticals mark the cut-points of light (0.0167 g), moderate (0.091 g) and vigorous-intensity activity (0.414 g)

fat percent and higher walking speed over both long and short distances, and the associations were statistically significant even at very low intensities. In addition, time spent in moderate-to-vigorous-intensity activity had a positive association with lower extremity functioning. More sedentary time was associated with higher fat percent and shorter distance walked in six minutes.

One of our main findings was that light activity was associated with fat percent both as a categorical and as a quasi-continuous measure. Two findings are especially noteworthy. First, the association of light activity with fat percent was almost as strong as that between moderate-to-vigorous activity and fat percent, even after adjusting for moderate-to-vigorous activity. Second, a moderately strong beneficial association was found even for very light-intensity activities. These findings may be explained by that fat percent is sensitive to aerobic activities of any intensity. We measured physical activity in older adults' normal daily life, and the monitors recorded activity during their daily chores. Light activities common to older adults, such as walking and habitual daily household activities, are well captured with accelerometers [20], and they can contribute substantially to the total energy expenditure [16]. Our findings add to the growing body of evidence, that even lower levels of accelerometer-measured physical activity are negatively associated with obesity among older adults [16].

Table 2 Partial correlations of physical activity in intensity categories with body composition and physical function

	Sedentary activity	Light activity		Moderate-to-vigorous activity	
	Model 1	Model 1	Model 2	Model 1	Model 3
Fat percent[a]	0.251***	−0.360***	−0.281***	−0.384***	− 0.312***
Appendicular lean mass[a]	0.006	−0.014	−0.018	0.010	0.015
6-min walk	−0.170**	0.279***	0.168**	0.465***	0.418***
10-m walk	−0.101	0.203**	0.122*	0.315***	0.273***
SPPB	−0.028	0.145**	0.086	0.220***	0.188**

Note
Abbreviations: 6-min walk = distance walked in 6 mins; 10-m walk = maximal walking speed over 10 m; *SPPB* Short Physical Performance Battery
Model 1: Controlled for sex and age
Model 2: Controlled for sex, age and moderate-to-vigorous activity
Model 3: Controlled for sex, age, and light activity
[a]Missing $n = 1$
*$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

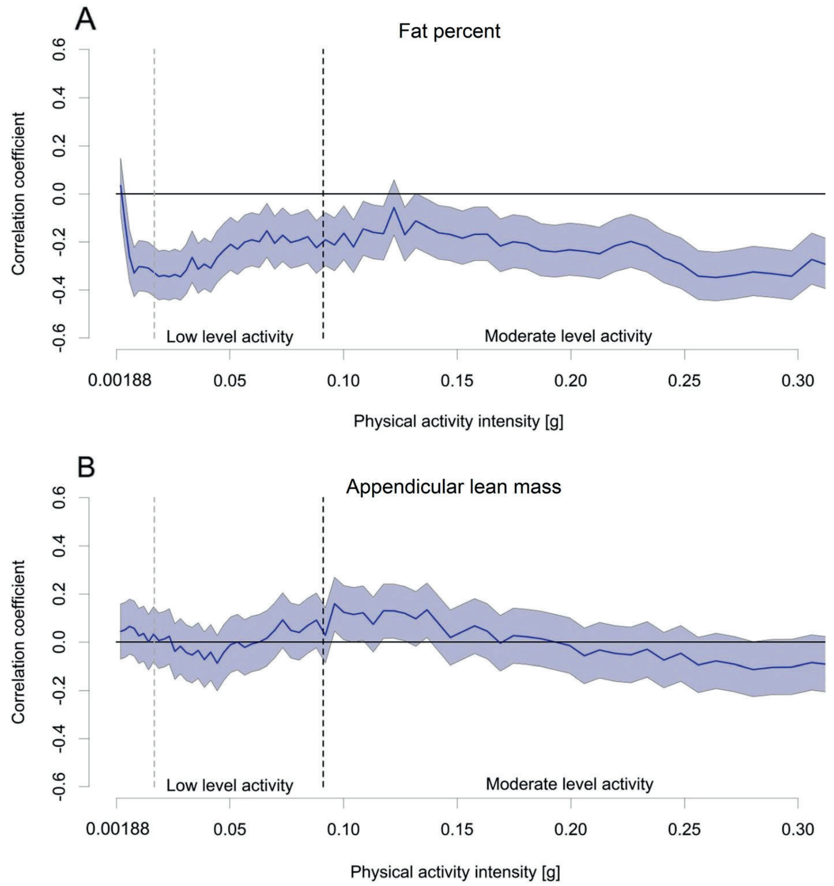

Fig. 3 Associations of physical activity intensities from 0.00188 to 0.31 g with body composition. Associations of mean daily minutes at each physical activity intensity bin with fat percent (**a**) and appendicular lean mass (**b**) are expressed as mean correlation coefficient r (y-axis, black line) and 95% confidence interval (CI, shaded area). Physical activity intensities are shown in the x-axis. Associations are statistically significant, if the 95% CI area does not cross the 0-line. Verticals mark the cut-points for light-intensity activity (0.0167 g) and moderate-intensity activity (0.091 g). Correlations are adjusted by sex and age

Interestingly, the association between physical activity and fat percent turned significantly negative already below the cut-point of light-intensity activity, which may have led to underestimation of the association between sedentary time and fat percent. This may indicate that the MAD cut-points defined and validated in healthy younger adults [25, 26] may have been too high in our study population. In a recent study, the optimal MAD cut-point to separate sitting from standing was suggested to be as low as 0.0033 g among children [32]. It may be that the previously defined cut-point of 0.0167 g for light-intensity activity [25] is too high among older adults. A common challenge in measuring physical activity among older adults is that accelerometers do not take into account the age-related decline in physiological functions [21] and the higher energy cost of walking in older age [33]. For example, the intensity of physical activity is often expressed in activity counts, and the most commonly used cut-point for moderate-intensity activity has been shown to underestimate activity intensity among many older adults [22]. Physical activity defined by the standard MAD cut-points may thus be more strenuous for older individuals. Our findings support the previously highlighted need for age-specific or individually tailored cut-points for physical activity intensities [22, 34].

Our finding that physical activity of any intensity was beneficially associated with walking speed over both long and short distance is remarkable, since performance in walking tests predicts disability, mobility limitation and deaths [35]. The association of moderate-to-vigorous-intensity activity with walking speed was expected and in line with previous cross-sectional studies (10–13). In contrast, light-intensity activity has been beneficially

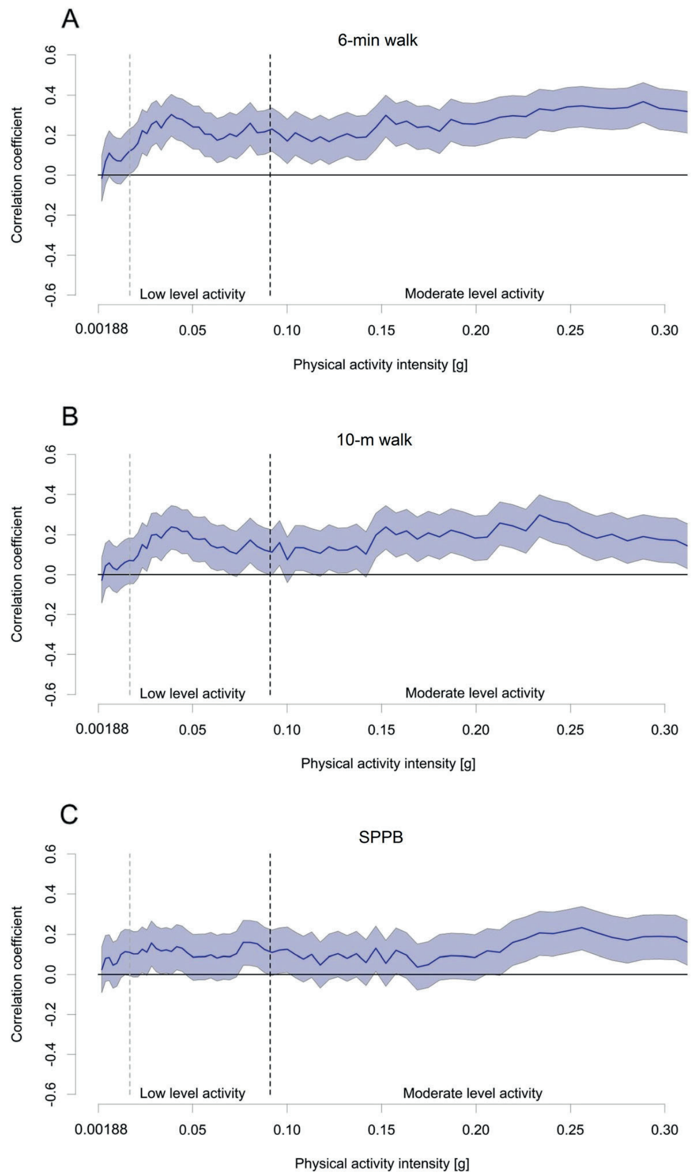

Fig. 4 Associations of physical activity intensities from 0.00188 to 0.31 g with physical function. Associations of mean daily minutes at each physical activity intensity bin with 6-min walking distance (**a**), maximal walking speed uver 10 m (**b**) and the SPPB (**c**) are expressed as mean correlation coefficient r (y-axis, black line) and 95% confidence interval (CI, shaded area). Physical activity intensities are shown in the x-axis. Associations are statistically significant, if the 95% CI area does not cross the 0-line. Verticals mark the cut-points for light-intensity activity (0.0167 g) and moderate-intensity activity (0.091 g). Correlations are adjusted by sex and age

associated with walking speed in some [10], but not all [9, 11] studies. One study found a significant association only in women [13]. In the present study, the associations of time spent in light activity with 6-min walk and 10-m walk were statistically significant even after adjusting for time spent in moderate-to-vigorous intensity activity suggesting that light-intensity activity has an independent positive association with walking speed. Another important finding was that even very light-intensity activity was associated with walking speed over both long and short distance. It is worth noting, that the associations of physical activity with walking speed turned positive, even though non-significantly, already below the cut-point for light activity. This may have led to underestimation of the association of sedentary time with walking speed, and can explain why we only found a significant association between sedentary time and 6-min walk whereas other studies have shown a significant association also between sedentary time and other walking tests [10–12]. The disparities may also be due to e.g., differences in study populations, walking tests utilized, physical activity assessment and analysis methods or the statistical analyses performed, which make comparing results from different studies somewhat complicated.

The positive association between accelerometer-based physical activity and walking speed is rational since maximal walking speed and walking endurance are both traits that are sensitive to habitual walking activity, which is common among older adults and well captured with accelerometers [20, 21]. In the present study, physical activity had stronger associations with 6-min walk than with 10-m walk. This may be explained by that 6-min walk represents steady state locomotion, the type of activity best captured with accelerometry, whereas short bursts of high-intensity activity similar to 10-m walk may be dissipated when the activity intensity is averaged into one-minute epochs [25]. Thus, the associations between physical activity and maximal walking speed should be investigated also in shorter epochs in the future.

The association between physical activity and lower extremity functioning assessed with the SPPB test was positive, but more distinct for higher intensities. This is not surprising, since the SPPB is a composite measure and assesses lower extremity strength and balance in addition to habitual walking speed [31]. Activity types that enhance these traits, such as resistance training and yoga, are not well captured with accelerometers [20, 21]. Resistance training is assumed to be more effective for muscle mass than aerobic exercise [6], which may also explain, why we, similar to Westbury et al. [14], did not find any association between physical activity and appendicular lean mass. It may also be that the cross-sectional study setting was not capable to reveal the associations between accelerometer-based physical activity and muscle mass, since Shephard et al. [15] found higher habitual physical activity level to be associated with better maintenance of muscle mass in a longitudinal study. Since accelerometry is limited in assessing the associations of physical activity with lower extremity functioning and muscle mass, utilizing PA diary in addition to accelerometry would be worthwhile, as well as conducting more longitudinal research. Future studies should also take into account participants' diet and nutrition, since adequate nutrient intake, including e.g., protein and vitamin D, is a key determinant of muscle mass and physical function [36].

We also found that the mean daily time spent within each of the investigated activity intervals declined drastically from very light to moderate-intensity activity, and the amount of vigorous activities was practically non-existing. Less than one third of participants had any activity exceeding 0.31 g, which correspondents to brisk walking (> 5.0 km/h) in a healthy adult population [26]. The mean daily times spent in sedentary and moderate-to-vigorous-intensity activities (10 h and half an hour, respectively) in the present study are in line with findings from recent reviews [19, 34]. This study adds to the literature knowledge about distribution of physical activity throughout the whole intensity range among older adults. Based on the findings from the present study and from the study among children from Gao et al. [32], it is necessary to further investigate especially the lower end of the intensity range and whether the previously defined cut-point to separate sedentary activities from light activities [25] is accurate among older adults.

Strengths and limitations

The strengths of this study include investigating the distribution of accelerometer-measured physical activity and evaluating the associations of physical activity with body composition and physical function along the whole intensity range. This was a novel analysis approach [21], which provided new information. Another strength is a relatively large, population-based sample of community-dwelling older adults, and assessment of several body composition and physical function variables, which all are meaningful and important for health and physical functioning and thus disability prevention among older adults.

This study also has its limitations. The study design of the XX-study required the participants to be sedentary or at most moderately active, but relatively healthy and community-dwelling, which limits generalizability of our results to all older adults. In agreement with the study design, the amount of higher-intensity activities was low, thus we cannot draw any conclusions on the associations of high-intensity physical activity with body composition and physical function. The activity level of participants was, however, higher than expected. It may be that participants did not consider e.g., walking errands as moderate-intensity activity, when they were initially interviewed for potential exclusion due to meeting the physical activity recommendations, and thus underestimated their physical activity level. According to the previous physical activity recommendations, participants self-reported at least moderate intensity activity bouts lasting at least 10 min. The accelerometer recordings, however, include moderate-to-vigorous intensity activity in bouts of any length, which may have led to higher amounts of moderate-to-vigorous activity than if it would have been investigated only in longer bouts. Third, it may be that participants were excited about the accelerometer measurements and increased their physical activity level during the measurement period. Future research is needed both among physically more active older adults as well as among more sedentary and less healthy and functioning older adults. On the other hand, exploration of this at most moderately active population did lend credence to the emergence that even small increments of light physical activity may confer health benefits to older adults [16].

Due to the cross-sectional nature of this study, any conclusions of causal relationships between physical activity and outcomes cannot be drawn. It may be, that favorable body composition and better physical function lead to higher levels of physical activity, and not vice versa. More longitudinal and experimental research is needed. Accelerometry has also some limitations, as noted previously. The analysis algorithm may neither have been sensitive enough to separate non-wear time from sedentary activities. In some cases, self-reported wear-time was excluded as non-wear time and self-reported non-wear time included as wear-time by the analysis algorithm. Investigating physical activity in detailed intensity ranges utilizing MADs is a novel analysis approach among older adults, and more research utilizing this analysis approach is required to verify the accuracy and applicability of the method.

Conclusion

In conclusion, the present study expands the understanding of amount and intensity of physical activity and the associations of physical activity with body composition and physical function along the whole intensity range among sedentary or at most moderately active older adults. We found that physical activity of any intensity was beneficially associated with fat percent and walking speed over both long and short distances. These findings provide additional evidence of the importance of encouraging older adults to engage in physical activity of any intensity. It may be that emphasizing moderate-to-vigorous-intensity activity is not feasible, since the majority of this population is unable to engage in high-intensity activities. Conclusive evidence shows, however, that physical activity of at least moderate intensity has a wide range of health benefits [4] and is required for preserving or improving cognitive functioning in older age [37]. To promote adaptation to physically active lifestyle, physical activity counseling among previously sedentary or at most moderately active older populations should thus initially highlight the benefits of increasing the amount of daily light-to-moderate-intensity activity. To gain greater benefits for health and functioning, older adults should be encouraged to increase the intensity of their habitual physical activity gradually. The relationships of light-intensity physical activity with body composition and physical function should be verified in future studies utilizing randomized controlled trial setting.

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Figs. 2, 3 and 4 were produced using project R (64-bit version 3.4.3, www.r-project.org).

Authors' contributions
All authors have made substantial contributions to the design of the study and the manuscript. TS was responsible for thinking up the design of the present study; collected, processed and analysed the data; interpreted the results; and drafted the manuscript. SS, RAF and TaR were responsible for the conception and design of the PASSWORD-study. SS and AT were responsible for designing and implementing the recruitment of participants. MA was responsible for designing the medical screening of participants. TiR was responsible for creating the raw acceleration data analysis script and contributed to the accelerometer data analysis. SS oversaw the overall execution of the PASSWORD-project. All authors revised the manuscript critically for important intellectual content and approved the final version to be published. All authors agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Availability of data and materials
The datasets used during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate
The study protocol was approved by the Ethics committee of the Central Finland Health Care District and the study was conducted in agreement with the Helsinki declaration. The participants signed an informed consent before participation.

Consent for publication
Not applicable.

Competing interests
Dr. Fielding reports grants from National Institutes of Health (National Institute on Aging) and the USDA, during the conduct of the study; grants, personal fees and other from Axcella Health, other from Inside Tracker, grants and personal fees from Biophytis, grants and personal fees from Astellas, personal fees from Cytokinetics, personal fees from Amazentis, grants and personal fees from Nestle', personal fees from Glaxo Smith Kline, outside the submitted work. For the remaining authors no conflicts of interest were declared.

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II

ASSOCIATIONS OF PHYSICAL ACTIVITY INTENSITIES, IMPACT INTENSITIES AND OSTEOGENIC INDEX WITH PROXIMAL FEMUR BONE TRAITS AMONG SEDENTARY OLDER ADULTS

by

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Associations of physical activity intensities, impact intensities and osteogenic index with proximal femur bone traits among sedentary older adults

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ABSTRACT

Background: Dynamic high-intensity physical activity is thought to be beneficial for older adults' bone health. Traditional volume-based processing of accelerometer-measured physical activity data, quantified on a minute-per-minute basis, may average out sporadic high impact activity, whereas accelerometer data processing approaches based on identifying impacts can capture also these potentially beneficial short activity bursts. We investigated the associations between habitual physical activity and proximal femur bone traits among sedentary older adults utilizing three different numerical treatments of accelerometer-data to examine, if impact-based processing approaches are more suitable to assess bone loading than volume-based processing of physical activity data among older adults.

Methods: This cross-sectional study utilized the baseline data from the PASSWORD-study ($n = 284$, mean ± SD age 74 ± 4 years, 57% women). Total femur bone mineral content (BMC) and bone mineral density (BMD), femoral neck BMC, BMD, section modulus and minimal width (MNW) were measured with dual energy x-ray absorptiometry. Physical activity was measured for seven consecutive days with a tri-axial accelerometer. Raw acceleration data was processed in three different ways and quantified as i) mean daily minutes in sedentary, light and moderate-to-vigorous-intensity activity, ii) mean daily number of acceleration peaks divided into low (1.5 g to 2.0 g), medium (2.0 g to 2.5 g) and high (>2.5 g) impacts, and iii) mean daily osteogenic index, which is a summary score calculated from log-transformed number of impact peaks in 32 intensity bands (≥1.3 g). Associations between physical activity measures and each bone trait were estimated with multiple linear regression adjusted with covariates (age, sex, weight, height, smoking, physical function, medication).

Results: Participants recorded on average 10 h sedentary, 2.5 h light and 33 min moderate-to-vigorous activity, and 3937 low, 494 medium and 157 high impacts per day. Mean osteogenic index score was 173. Light physical activity was positively associated with all bone traits (beta = 0.147 to 0.182, $p < 0.001$ to $p = 0.005$) except MNW. Sedentary or moderate-to-vigorous activity, low, medium or high impacts or osteogenic index were not associated with any bone parameter.

Conclusions: Light physical activity may decelerate the age-related bone loss in older adults who do not meet the physical activity recommendations. In this population, the amount of high impact activity may be insufficient to stimulate bone remodelling.

1. Introduction

Life-long physical activity is one of the major non-pharmacological methods to prevent and treat osteoporosis [1–3] but the evidence on which exact types and intensities of exercise are sufficient to promote bone health in older age is still inconsistent [4]. Notably, specific prescription of physical activity for bone health for older people is conspicuously absent from the current American physical activity recommendations [5]. Impact activities including hopping and jogging are likely to have higher osteogenic potential than habitual walking also for older adults [6]. However, the majority of older adults do not engage in high-intensity physical activity, but prefer light activities such as walking [7].

Findings on the associations between accelerometer-based physical

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activity and bone parameters in older adults are scarce and inconclusive. Some [8,9], but not all [10,11], studies have shown a positive association between moderate-to-vigorous intensity physical activity and femoral neck bone parameters. However, accelerometer-data is usually averaged into mean intensity of each 15–60 s epoch, which may artificially prevent the ability to detect potentially osteogenic high-impact activity, which may occur in short bursts [12,13], such as in stair climbing. Therefore, other accelerometer-data processing approaches are necessary to investigate bone loading physical activity.

A few alternative raw acceleration data processing approaches appropriate for bone loading evaluation have been developed, which capitalise on the physiological understanding that bone responds to strain magnitude and rate [14,15]. For example, Ahola and colleagues [12] presented a method based on identifying all impact peaks present in a prolonged accelerometry recording. The osteogenic index, also known as daily impact score, is then calculated by dividing the impact peaks into 32 intensity bands (from 1.3 to 10 times body weight) based on the maximum acceleration of the peak. Subsequently the number of peaks in the bands are summed together with each band weighted with the logarithm of the peaks within it [12]. A more straightforward approach is to summarize the amount of acceleration peaks within a specified number of intensity bands, and use the count within each band as a measure [16–19].

Osteogenic indices have been shown to be associated with bone traits in premenopausal [12] and postmenopausal women [20]. Even a low volume of high impacts corresponding to jogging or running has been beneficially associated with bone traits in adolescents [21], premenopausal [19,22], postmenopausal [22] and older women [18]. While a minimal impact threshold of around 5 times body weight has been identified for adolescents and young and middle-aged adults for positive bone adaptations [19,21], it has been proposed that lower-intensity impacts may create similar mechanical strains and thus be associated with better bone health among older people as higher intensity activity among younger people [16,18,22]. However, studies among older men are lacking altogether, and a dearth of research is to be found with older women as well.

Among older adults, the amount of high intensity impacts has been very low in earlier studies [17,18,23]. We have previously investigated the amount of physical activity accumulated through the gradation of intensities among older men and women who were at most moderately active by self-report [24]. We observed that less than one third of participants recorded any activity at intensities corresponding to walking faster than 5 km/h during the measurement week and the amount of activity corresponding to jogging was, for all intents and purposes, non-existing [24]. However, in that study the raw acceleration data were averaged into one-minute epochs, and the amount of impacts remained unknown. Therefore, the purpose of this cross-sectional study was to investigate the amount of potentially osteogenic high-impact activity and the associations of accelerometer-based physical activity with proximal femur bone traits among older men and women who did not meet physical activity recommendations. We utilized three different accelerometer-data processing approaches. First, we divided physical activity into sedentary, light and moderate-to-vigorous intensity activity [13]. Then we calculated the amount of low, medium and high impacts [16] and finally, the osteogenic index [12]. Based on the previous literature, we hypothesized that osteogenic index and the amount of high impacts would be more strongly associated with bone properties than the volume-based (minutes of activity within a particular intensity range) physical activity measure.

2. Materials and methods

2.1. Study design and participants

This cross-sectional study utilized the baseline data of the Promoting safe walking among older people (PASSWORD, ISRCTN52388040)–study. Study design and recruitment process have been described in detail by Sipilä et al. [25] and the study flow for baseline measurements by Savikangas et al. [24]. Briefly, participants were eligible for the study if they were 70–85 years old, community-dwelling, lived in the city of Jyväskylä, Finland, did not meet the current physical activity recommendations by self-report (less than 150 min of walking/week and no regular resistance training), could walk 500 m without assistance, and scored ≥24 points in the Mini Mental State Examination (MMSE) test. Exclusion criteria were severe chronic condition and/or medication, behavioural factor that could have compromised participation in the study, severe vision or hearing problem, heavy alcohol consumption, and other family member participating in the PASSWORD-study. From the initial random sample of 3862 people drawn from the Finnish national population registry, 2684 could be contacted by phone. Of them, 401 were invited to laboratory measurements after an initial screening interview, and finally 314 were recruited to the study after additional review of the exclusion criteria at the laboratory. The final sample for the present study included 284 participants with acceptable data on accelerometer-measured physical activity and bone properties.

This study has been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki). The study protocol was approved by the Ethics committee of the Central Finland Health Care District (14/12/2016, ref: 11/2016). Informed consent was obtained from all individual participants included in the study.

2.2. Measurements

2.2.1. Bone properties

Femoral neck and total proximal femur bone mineral content (BMC, g), bone mineral density (BMD, g/cm^2) and the T-score were measured with dual energy X-ray absorptiometry (DXA, LUNAR Prodigy, GE Healthcare, Madison, WI, USA). Subsequently, femoral neck section modulus (SM [mm^3], an index of bending strength) and minimal neck width (MNW [mm], an outer diameter of the bone) at the narrowest femoral neck section were calculated with advanced hip structural analysis (AHA). Based on the femoral neck T-score participants were categorize as normal (≥−1), osteopenic (<−1 to >−2.5) or osteoporotic (≤−2.5) [1,26]. Mean values of the bone traits in both femurs were calculated. For participants with hip replacement on either side, the scan of the non-operated side was used. Participants with hip replacement on both sides were excluded.

Participants were scanned in supine position in the centre of the table using the default-scanning mode automatically selected by the Prodigy software (Lunar Prodigy Advance Encore v. 14.10.022). Standard procedures of the device manufacturer were followed and the device was calibrated with a phantom every morning prior to the measurements for quality assurance. Images were controlled prior to the analyses to ensure right definition of the femoral neck section. As for two participants, scans of one femur were excluded due to failed definition of femoral neck section, and the values for the other side were used. Coefficients of variation (CV%) for different femoral neck properties have been reported to vary approximately between 2 and 10%, SM having the highest CV of 10.1% [27]. In our laboratory, the CV% for SM has been reported to be 5.1% [28] and the root mean square coefficient of variation (CV_{RMS}) for femoral neck BMC 0.6% [29].

2.2.2. Physical activity

Tri-axial accelerometer (UKK RM42, UKK, Tampere, Finland) was used to measure physical activity. Participants were instructed to wear the accelerometer in an elastic waistband on their right side of the hip during waking hours, except during water activities. For all accelerometer-data processing approaches, all three axes were included by using the resultant (Euclidian norm, $\sqrt{x2 + y2 + z2}$) acceleration in data processing. We have described the numerical approach used to divide the 24 h hour minute by minute recordings into sedentary (less than 0.0167 multiples of gravity [g]), light (0.0167 g to 0.091 g), moderate (0.091 g to 0.414 g) and vigorous (0.414 g or more) categories in a previous publication from the same dataset [24]. Briefly, the resultant was taken from each 3D sample, mean amplitude deviation was then calculated in non-overlapping 5 s epochs, and the mean of 12 consecutive epochs was used to produce a minute-by-minute intensity array from mid-night to mid-night. The array was then transformed into a histogram with the aforementioned bin cut-offs to produce daily minutes spent in the four categories, and the mean of all included days (at least 3 days with at least 10 h wear-time was required to be included in statistical analyses) is given as the result. Due to the very limited amount of vigorous activity, moderate and vigorous intensity activities were combined into one category for further analysis. The processing approach and cut-offs have been validated among younger adults [13,30].

Our in-house implementation of Deere and colleagues [16] acceleration peak calculation was used to identify each sample of the resultant acceleration recording, which was higher than the preceding and the subsequent sample as an acceleration peak. The magnitude, and the time stamp of the peak were noted. The peaks were then divided into 24 h epochs, and a three category histogram (low [1.5 g to 2.0 g]; medium [2.0 g to 2.5 g]; high [higher than 2.5 g]) was calculated to represent each day. The mean of days selected for physical activity evaluation is reported as the outcome.

Our in-house implementation of Ahola and colleagues [12] osteogenic index calculation was used to calculate an osteogenic index for each 24 h period of recording and the mean of each included day is reported as the outcome. We have described our implementation in a previous publication [31]. Briefly, the norm (resultant) of each sample was calculated and the data was subsequently considered in 24 h epochs from mid-night to mid-night. All continuous peaks above 1.3 g were identified, and the maximum value of a given peak was noted. The resulting peak array was transformed into 32 bin histogram from 1.3 to 10.3 g with values higher than 10.3 g assigned to the final bin. The daily osteogenic index was then calculated as the sum of the logarithm of peaks in a bin multiplied by the lower cut-off of a given bin.

2.2.3. Covariates

Sex and date of birth were drawn from population registry, and age in years at the laboratory visit day was calculated. Body weight (kg) and height (cm) were measured with standard procedures and body mass index (BMI, kg/m^2) was calculated. Physical functioning was assessed with the Short Physical Performance Battery (SPPB), which consists of four meters habitual walking speed, five time chair rise time and standing balance tests [32]. Information on current medication use, including hormone replacement therapy, bisphosphonates and oral glucocorticoids, was collected by self-report at nurse's examination and verified from the integrated patient information system utilized by the national health services (Effica database) by the study physician. All non-vaginal preparations including oestrogen were considered as hormone replacement therapy. Smoking history was self-reported and categorized as current smoker, former smoker (smoked at least 100 times during lifetime, but reported no current smoking), or never smokers (smoked <100 times during lifetime).

2.3. Statistical analyses

Descriptive data are presented as means and/or medians with standard deviations (SD) and/or inter-quartile range (IQR) for continuous variables and frequencies (n) and percentages (%) for categorical variables in all participants and for men and women separately. To illustrate the distribution of impacts within each intensity band utilized to calculate osteogenic index, logarithm of the mean daily amount of impacts at each level from 1.3 g onwards is presented in a histogram. Based on visual inspection, medium and high impacts were skewed to the right and thus log-transformed for further analyses. In addition, Kolmogorov-Smirnoff –tests indicated moderate-to-vigorous intensity activity, low impacts and osteogenic index to have skewed distributions. As for these physical activity variables, initial analyses were therefore performed with both original and log-transformed values. Since the results did not differ, original values were used in the analyses.

Associations of physical activity variables with each others were assessed using Pearson's correlation coefficient r. Associations of proximal femur bone traits with physical activity were tested utilizing multiple linear regression. Separate models were built for each bone trait and each physical activity variable. Models were adjusted with factors known to be associated with bone health and/or physical activity, including sex, age, weight, height, smoking status, SPPB score, hormone replacement therapy, oral glucocorticoids, and bisphosphonates. All variables were tested for multicollinearity. To adjust the associations of physical activity intensities and impact intensities with other intensity bands, a second set of models was built, one including sedentary, light and moderate-to-vigorous intensity activity and all covariates, and the second including low, medium and high impacts and all covariates. Additional sensitivity analyses were performed, in which all participants using hormone replacement therapy, bisphosphonates or oral glucocorticoids were excluded. Statistical analyses were performed with IBM SPSS Statistics 26 (SPSS Inc., Armonk, NY). Statistical significance level was set at 0.05 for all analyses.

To investigate the strength of the associations of impacts within each intensity band utilized to calculate osteogenic index, partial correlation coefficients were calculated for log-transformed number of impacts within each intensity band and each bone variable. Correlations were adjusted with those covariates that had $p < 0.1$ in some of the regression models of the bone variable in question. Results are presented in graphs as correlation coefficient r and 95% confidence interval (CI). The graphs were created with RStudio version 1.2.1335 (RStudio Inc., Boston, MA).

A priori power analyses were calculated as for the main outcome, 10 m maximal walking speed, of the PASSWORD-study [25]. Additional post hoc power calculations were performed for the present study. For the studied variables, a sample size of 284 yields a power over 98% to show a contribution to the explained variance of 10% in a linear regression model with 10–12 predictors (including interactions, but not constant) if the probability level (alpha) is set at 0.05. Sample size of 284 yields even weak correlation coefficients ($r = 0.12$) statistically significant ($p < 0.001$, two-tailed).

3. Results

Descriptive data of participant characteristics are presented in Table 1. Mean age was 74 years, and 57% were women. Mean BMC at the femoral neck was 4.442 g and mean BMD 0.905 g/cm^2. Nearly half of the participants had femoral neck T-score below −1, which indicates potential osteopenia.

Participants spent on average 10 h per day sedentary, 2.5 h in light activity and half an hour in moderate-to-vigorous activity. Participants had on average (median; IQR) 3937 (4591; 2103–5177) low, 494 (347; 164–662) medium and 157 (112; 70–181) high impacts per day. Mean osteogenic index score was 173 (Table 1). The distribution of log-transformed mean daily number of impacts throughout the intensity range utilized to calculate osteogenic index is presented in Fig. 1. The average amount of impacts within each intensity band decreased from over 5000 impacts in the 1.3 to <1.5 g bin to less than 10 daily impacts in the 3.1 to <3.3 g bin. The mean amount of impacts within each bin exceeding the intensity of 6.1 g was less than one, except in the last bin including all impacts of ≥10.3 g.

Bivariate correlations between physical activity variables are shown in Table 2. Strongest associations ($r > 0.7$) were observed between moderate-to-vigorous activity and low impacts, low and medium impacts, medium and high impacts, and osteogenic index and high impacts.

The associations of proximal femur bone traits with physical activity

Table 1
Descriptive statistics of study participants in the whole sample and according to sex (mean ± SD or n (%)).

	All (n = 284)	Men (n = 121)	Women (n = 163)
Age, years	74.4 ± 3.8	74.3 ± 3.9	74.4 ± 3.7
Height, cm	166 ± 9	173 ± 6	161 ± 6
Weight, kg	76.9 ± 14.4	83.9 ± 12.4	71.7 ± 13.5
BMI, kg/m^2	27.9 ± 4.8	27.8 ± 3.6	27.9 ± 5.5
SPPB, total score[a]	10.3 ± 1.5	10.6 ± 1.5	10.0 ± 1.5
Smoking status, n (%)			
Never	175 (62)	55 (46)	120 (74)
Former	98 (35)	57 (47)	41 (25)
Current	11 (4)	9 (7)	2 (1)
Medication			
Hormone replacement therapy, n (%)	23 (8)	–	23 (14)
Bisphosphonates, n (%)	2 (1)	–	2 (1)
Glucocorticoids, n (%)	12 (4)	5 (4)	7 (4)
Femoral neck T-score			
≤−1.0, n (%)	138 (49)	64 (53)	74 (45)
≤−2.5, n (%)	11 (4)	7 (6)	4 (3)
Proximal femur bone traits			
Femoral neck BMC, g[b]	4.442 ± 0.995	4.967 ± 0.996	4.053 ± 0.798
Femoral neck BMD, g/cm^2[c]	0.905 ± 0.132	0.932 ± 0.137	0.885 ± 0.124
Total femur BMC, g[b]	34.887 ± 7.002	39.429 ± 6.588	31.408 ± 5.056
Total femur BMD, g/cm^2[c]	0.994 ± 0.150	1.037 ± 0.155	0.962 ± 0.138
SM, mm^3[d]	664.6 ± 182.7	807.5 ± 162.5	558.5 ± 110.4
MNW, mm[e]	32.7 ± 3.3	35.5 ± 2.7	30.7 ± 2.1
Accelerometer-based physical activity			
Days included	6.6 ± 0.8	6.7 ± 0.7	6.6 ± 0.8
Wear time, h/d	14.1 ± 1.3	14.3 ± 1.3	13.9 ± 1.2
Physical activity in intensity categories, min/d			
Sedentary activity	603 ± 82	627 ± 81	585 ± 79
Light activity	210 ± 66	197 ± 61	219 ± 68
Moderate-to-vigorous activity	33 ± 20	33 ± 21	33 ± 20
Impacts, no.			
Low impacts	3937 ± 2426	4017 ± 2468	3877 ± 2400
Medium impacts	494 ± 463	479 ± 432	504 ± 487
High impacts	157 ± 154	165 ± 188	151 ± 122
Osteogenic index, score	173 ± 47	169 ± 47	176 ± 47

[a] Short physical performance battery.
[b] Bone mineral content.
[c] Bone mineral density.
[d] Section modulus (Z).
[e] Minimal neck width.

and impact intensities and osteogenic index are presented in Tables 3–4. Light physical activity was positively associated with femoral neck BMC and BMD, total femur BMC and BMD and with SM (beta = 0.147 to 0.182, $p < 0.001$ to $p = 0.005$), but not with MNW (Table 3). Ten minutes increase in mean daily light activity was associated with 0.024 g higher femoral neck BMC and 0.003 g/cm^2 higher femoral neck BMD. Sedentary time or moderate-to-vigorous activity were not associated with any bone trait. When adjusted with other intensity bands, light physical activity remained positively associated with all bone traits (beta = 0.144 to 0.180, $p < 0.001$ to $p = 0.010$) except MNW, whereas no statistically significant associations were found for sedentary or moderate-to-vigorous intensity activity (Table 4). The results did not change, when all hormone replacement therapy, bisphosphonate and oral glucocorticoid users were excluded: light activity remained significantly and positively associated with all bone parameters ($p < 0.001$ to $p = 0.010$, data not shown) except MNW when investigated as single physical activity variable in the model. When adjusted with other bands, the positive association with MNW became statistically significant, too ($p = 0.038$, data not shown). Sedentary or moderate-to-vigorous activity were not associated with any bone parameter in the sensitivity analyses either.

Low, medium or high impacts were not associated with any bone trait when investigated in separate models ($p > 0.09$ for all, Table 3). In the sensitivity analyses excluding all hormone replacement therapy, bisphosphonates and oral glucocorticoid users and only one impact intensity in the model at a time, low impacts were positively associated with total femur BMD (beta = 0.130, $p = 0.048$, data not shown). When adjusted with other impact intensity bands, low impacts were positively associated with femoral neck BMD (beta = 0.186, $p = 0.025$) and negatively with MNW (beta = −0.117, $p = 0.038$), and this result was replicated in the sensitivity analyses (data not shown). Medium or high impacts were not associated with any bone trait in any model.

Osteogenic index was not associated with any bone trait ($p > 0.3$ for all, Table 3), which did not change in the sensitivity analyses excluding all hormone replacement therapy, bisphosphonates and oral glucocorticoids users (data not shown). Associations of log-transformed number of impacts within each intensity band utilized to calculate osteogenic index with femoral neck BMC, BMD and SM are presented in Fig. 2 (data for total femur BMC and BMD and MNW not shown). Impacts of any intensity were not associated with any bone variable, when the associations were adjusted for covariates.

4. Discussion

We examined the associations of physical activity with proximal femur bone traits among sedentary older men and women utilizing three different approaches to process the raw acceleration data. We found that light intensity physical activity was positively associated with femoral neck and total femur bone mineral content and density and with section modulus, which indicates femoral neck bending strength. In contrast, neither sedentary or moderate-to-vigorous activity nor any of the two impact peak-based methods were significantly associated with bone health. That is, high impacts or osteogenic index were not better predictors of bone health among sedentary older adults than other physical activity measures, in contrast to what was hypothesized.

We found that light intensity activity was consistently positively associated with all other proximal femur bone traits except femoral neck minimal width in all models, which is in contrast to the previous literature indicating relatively high-magnitude impact peaks [17,18,20] and moderate and vigorous activities [8,9,33] as positive predictors of proximal femur bone traits. Only a few previous studies have investigated the associations between light physical activity and proximal femur bone traits in older adults, with no significant associations found [8,10,33,34]. Chastin and colleagues [35] have shown a significant positive association between light activity and femoral neck BMD in women in a general adult population including also older adults. In contrast, based on previous research [18–20,22] we hypothesized that high impacts and osteogenic index would be beneficially associated with bone measures, but did not observe any relationship. Similarly to the present study, Hannam and colleagues [18] did not find any significant associations between impacts of any intensity and hip BMD among a comparable cohort of older women. In contrast, they found high impacts to be positively and low/medium impacts negatively associated with hip structural measures in some adjusted models, yet the observed significant associations were weak. This was presumed to be due to low amount of high impacts or the low threshold utilized to categorize high impacts [18]. In the present study, the mean daily amount of high impacts was tenfold compared to the study of Hannam et al. [18]. It may thus be, that the intensity of high impacts classified as per Deere and colleagues [16] is not sufficient for osteogenesis, even though this amount could have been expected to be sufficient based on the findings by Stiles and colleagues [22]. They observed that the osteogenic threshold was lower among post- than among premenopausal women, which could have indicated even lower threshold among older adults

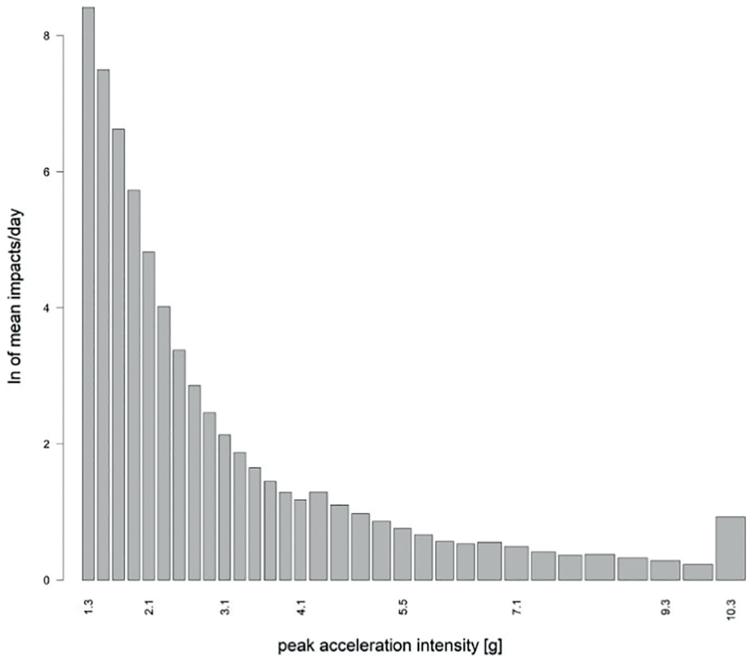

Fig. 1. Log-transformed number of mean daily impacts at each intensity band. Y-axis values stand for the lower limit of each intensity band, the values utilized to calculate osteogenic index.

Table 2
Pearson's correlation coefficients (r) between physical activity variables.

	Light activity	Moderate-to-vigorous activity	Low impacts	Medium impacts	High impacts	Osteogenic index
Sedentary activity	−0.502***	−0.380***	−0.368***	−0.325***	−0.265***	−0.295***
Light activity		0.319***	0.441***	0.342***	0.296***	0.373***
Moderate-to-vigorous activity			0.873***	0.665***	0.491***	0.496***
Low impacts				0.724***	0.542***	0.547***
Medium impacts					0.765***	0.598***
High impacts						0.842***

*** $p < 0.001$.

Table 3
Associations of accelerometer measured physical activity with proximal femur bone traits from multiple linear regression analysis adjusted with sex, age, weight, height, SPPB score, smoking status and use of hormone replacement therapy, bisphosphonates and oral glucocorticoids. Values are presented as standardized beta coefficients.

	Sedentary time		Light activity		Moderate-to-vigorous activity		Low impacts		Medium impacts		High impacts		Osteogenic index	
	Beta	p	Beta	p	Beta	p	Beta	p	Beta	p	Beta	p	Beta	p
Femoral neck BMC[a]	−0.076	0.122	0.158	0.002	0.055	0.297	0.078	0.155	0.048	0.352	0.030	0.542	0.046	0.351
Femoral neck BMD[b]	−0.062	0.279	0.165	0.005	0.025	0.676	0.080	0.206	−0.039	0.512	−0.056	0.321	−0.009	0.875
Total femur BMC[a]	−0.070	0.112	0.148	0.001	0.040	0.392	0.080	0.097	0.039	0.394	0.007	0.870	0.040	0.349
Total femur BMD[b]	−0.083	0.137	0.182	0.001	0.026	0.663	0.102	0.094	0.020	0.736	−0.026	0.629	0.023	0.671
SM[c]	−0.034	0.414	0.147	<0.001	0.007	0.878	0.004	0.928	−0.033	0.441	−0.005	0.905	0.019	0.644
MNW[d]	0.022	0.458	0.053	0.194	0.002	0.968	−0.062	0.148	0.008	0.847	0.024	0.526	0.008	0.844

[a] Bone mineral content, g.
[b] Bone mineral density, g/cm^2.
[c] Section modulus (Z), mm^3.
[d] Minimal neck width, mm.

[22].

In contrary to Hannam et al. [18], we found that low impacts were positively associated with hip BMD. The association was, however, statistically significant only when adjusted for other impact intensities. On the other hand, the association between femoral neck width and low impacts was negative, when other impact bands were included in the model. These contrasting findings must be interpreted with caution due to high collinearity of impacts within different intensity bands. As for

Table 4
Associations of accelerometer measured physical activity intensities (Model 1) and impact intensities (Model 2) with proximal femur bone traits from multiple linear regression analysis adjusted with sex, age, weight, height, SPPB score, smoking status and use of hormone replacement therapy, bisphosphonates and oral glucocorticoids. Values are presented as standardized beta coefficients.

	Model 1						Model 2					
	Sedentary time		Light activity		Moderate-to-vigorous activity		Low impacts		Medium impacts		High impacts	
	Beta	p	Beta	p	Beta	p	Beta	p	Beta	p	Beta	p
Femoral neck BMC[a]	−0.004	0.950	0.152	0.008	0.024	0.659	0.078	0.283	0.009	0.926	−0.010	0.890
Femoral neck BMD[b]	0.010	0.880	0.170	0.010	−0.004	0.952	0.186	0.025	−0.102	0.326	−0.065	0.448
Total femur BMC[a]	−0.005	0.928	0.144	0.004	0.011	0.814	0.093	0.145	0.020	0.799	−0.049	0.455
Total femur BMD[b]	−0.010	0.877	0.180	0.005	−0.011	0.859	0.157	0.053	−0.001	0.988	−0.095	0.250
SM[c]	0.034	0.477	0.165	<0.001	−0.013	0.774	0.047	0.434	−0.096	0.198	0.043	0.381
MNW[d]	0.068	0.138	0.082	0.070	0.010	0.811	−0.117	0.038	0.046	0.519	0.043	0.456

[a] Bone mineral content, g.
[b] Bone mineral density, g/cm^2.
[c] Section modulus (Z), mm^3.
[d] Minimal neck width, mm.

the femoral neck width, biological covariates, including sex, age and height, may determine the bone structure to the extent that associations with physical activity variables remain imperceptible.

Bone mass and strength decline with increasing age [36], and some researchers have proposed that lower impacts may create similar strains in older and weaker bones as higher impacts create in younger and stronger bones [16]. In contrast, we have observed a reversed trend between maximal performance and skeletal robustness in cross-sectional studies compared to the suggestion by Deere and colleagues [16], i.e. we found that younger men were able to produce higher maximal forces with respect to tibial robustness in jumping compared to older men [37], and that the relationship between jumping performance and tibial robustness was similar between pre- and postmenopausal women albeit the marked bone loss associated with menopause [38]. In addition to magnitude of the strains, another crucial element of bone loading physical activity is the frequency of the strains [39]. In the present study, the amount of impacts exceeding 4.9 g, which has been considered sufficient to promote bone health in adolescents and younger adults [19,21], was very low. It is thus plausible, that the impacts have not occurred as cycles with sufficient length and frequency to stimulate bone remodelling. However, it has also been proposed, that low-force exercises may cause sufficient strains to maintain the so-called conservation mode [40] and that habitual physical activity may influence the rate of age-related bone loss [41]. This is supported by a meta-analysis showing that long-term walking interventions prevent age-related bone loss [42]. Thus, it could be that continuous and large amounts of accelerometer-based light activity can create sufficient strains or micro damage to avoid dropping to disuse-mode with excessive bone resorption, and decelerate the age-related bone loss. It may be that sedentary older adults, who do not meet the physical activity recommendations, benefit from continuous loading in means of large amounts of habitual upright ambulatory activities that are classified as light physical activity.

Even though light intensity activity only explained approximately 2% of variation in bone parameters, an increase of 10 min of light intensity activity per day was associated with 0.3% higher hip BMD. This corresponds almost to the average yearly decline of 0.5% in BMD in this age group [36]. Increasing light intensity physical activity might thus be a feasible way to prevent the age-related loss of bone among sedentary older adults. It is, however, important to bear in mind that the benefits of high intensity resistance exercise alone and combined with impact activity for older adults' bone health are well documented [4,43]. Higher intensity activities should therefore be preferred, if possible and safe. Future longitudinal and intervention studies are required to confirm, if light intensity physical activity has positive effect on bone health among sedentary older adults.

This study has several limitations. The cross-sectional study design does not allow to draw any conclusions on the causal effects of habitual physical activity on bone health. In accordance with the inclusion criteria of the PASSWORD-study, the amount of high impacts was very small. It is therefore not possible to draw conclusions on, if greater amount of high impacts would be beneficially associated with bone health also in older age. In addition, the study sample was relatively small, which may have led to limited power to detect associations between small numbers of high impacts with bone traits. The study population was also relatively healthy but at most moderately physically active, thus the results cannot be generalized to all older adults. Furthermore, bone measurement was limited to DXA-scan of the femurs. Additional bone characterisations would have given a wider understanding of the associations between physical activity and bone properties. For example, any lumbar spine measurements were not obtained, and future studies are required to investigate if high impact activity is associated with lumbar spine health among older adults. Finally, many lifestyle and environmental factors during life-course, which determine bone health, could have affected the results. It may, for example, be that those participants who have earlier in their lives engaged in more intense physical activity and thus gained good bone health, have maintained higher level of lighter activity in old age. Healthy diet – especially sufficient intake of vitamin D and calcium – is crucial for bone health, but nutrient intake could not be controlled for in the present study. It has also been suggested that lean body mass mediates the association between physical activity and bone health [34] and it would have been worthwhile to adjust the models with body composition instead of body weight. Due to high collinearity between lean body mass and two important predictors of bone strength and structure, sex and height, this was not possible in the present study.

5. Conclusion

In summary, we found that light intensity physical activity was positively associated with bone health among sedentary older adults, whereas any measure of high intensity or high impact activity was not. In light of these results, older adults with sedentary lifestyles should be encouraged to replace sedentary time with light upright ambulatory activities to avoid bone disuse mode and prevent excessive bone loss, even though high intensity activities should be preferred when they are possible and safe to perform. However, longitudinal research is required to confirm our findings that light physical activity may ameliorate the age-related bone loss among older adults, who do not meet the physical activity recommendations in means of at least moderate intensity activity and strength training. In this population, the amount of high impact activity may be insufficient to stimulate bone remodelling. It would be worth testing, whether high-impact activity was effective in this population of at most moderately physically active, but relatively healthy community-dwelling older adults. In addition, associations of

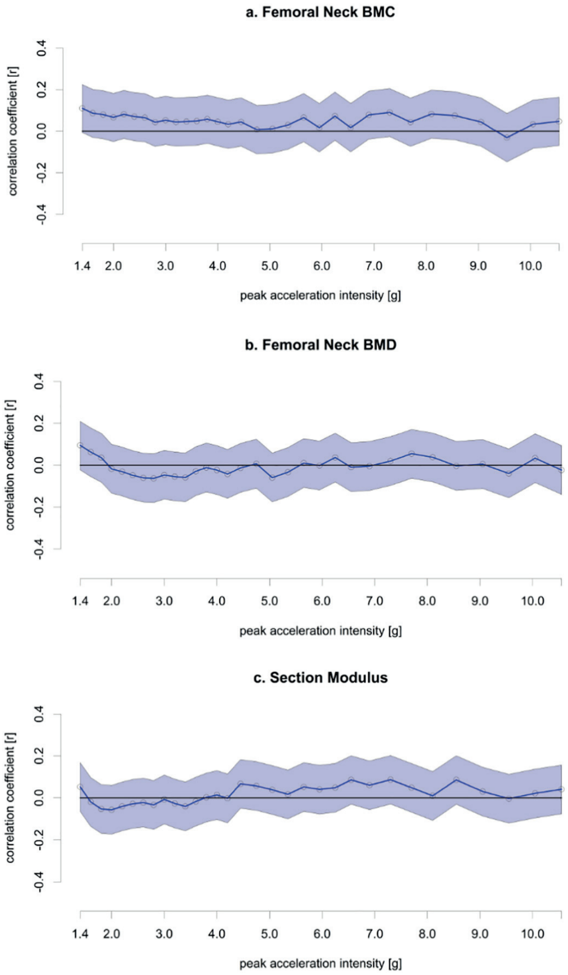

Fig. 2. Associations of mean daily number of impacts at each intensity band (x-axis) utilized to calculate osteogenic index with femoral neck bone traits, presented as partial correlation coefficient r (y-axis, black line) and 95% confidence interval (CI, shaded area). a) for BMC (adjusted for weight, height and smoking status); b) for BMD (adjusted for weight, age, the SPPB score and use of hormone replacement therapy); and c) for section modulus (adjusted for weight, height, sex and smoking status).

osteogenic index and impact intensities should be investigated in more active older populations and in physical activity intervention settings among older adults.

CRediT authorship contribution statement

Tiina Savikangas: Conceptualization, Formal analysis, Methodology, Investigation, Writing - original draft. **Sarianna Sipilä:** Conceptualization, Funding acquisition, Investigation, Writing - review & editing, Supervision. **Timo Rantalainen:** Conceptualization, Software, Writing - review & editing, Supervision.

Declaration of competing interest

Authors declare no conflict of interest.

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III

THE IMPACT OF MULTIMORBIDITY PATTERNS ON PHYSICAL ACTIVITY AND PHYSICAL CAPACITY AMONG OLDER ADULTS PARTICIPATING IN A YEAR-LONG EXERCISE INTERVENTION

by

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IV

THE EFFECTS OF A PHYSICAL AND COGNITIVE TRAINING INTERVENTION VS. PHYSICAL TRAINING ALONE ON OLDER ADULTS' PHYSICAL ACTIVITY: A RANDOMIZED CONTROLLED TRIAL WITH EXTENDED FOLLOW-UP DURING COVID-19

by

Savikangas T., Törmäkangas T., Tirkkonen A., Alen M., Fielding R.A., Kivipelto M., Rantalainen T., Stigsdotter Neely A. & Sipilä S. 2021

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RESEARCH ARTICLE

The effects of a physical and cognitive training intervention vs. physical training alone on older adults' physical activity: A randomized controlled trial with extended follow-up during COVID-19

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Abstract

Background

Executive functions underlie self-regulation and are thus important for physical activity and adaptation to new situations. The aim was to investigate, if yearlong physical and cognitive training (PTCT) had greater effects on physical activity among older adults than physical training (PT) alone, and if executive functions predicted physical activity at baseline, after six (6m) and twelve months (12m) of the interventions, one-year post-intervention follow-up and an extended follow-up during COVID-19 lockdown.

Methods

Data from a single-blinded, parallel-group randomized controlled trial (PASSWORD-study, ISRCTN52388040) were utilized. Participants were 70–85 years old community-dwelling men and women from Jyväskylä, Finland. PT (n = 159) included supervised resistance, walking and balance training, home-exercises and self-administered moderate activity. PTCT (n = 155) included PT and cognitive training targeting executive functions on a computer program. Physical activity was assessed with a one-item, seven-scale question. Executive functions were assessed with color-word Stroop, Trail Making Test (TMT) B-A and Letter Fluency. Changes in physical activity were modeled with multinomial logistic models and the impact of executive functions on physical activity with latent change score models.

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Data Availability Statement: The data come from the Promoting safe walking among older people (PASSWORD) study led by the University of Jyväskylä. The data are restricted by the Ethical Committee of the Central Finland Health Care District. Dissemination of data set outside of the PASSWORD research team is prohibited. However, ethically compliant dataset can be made available upon request. Data requests may be sent to the

Ethics Committee of the Central Finland Health Care District, Päivi Lampinen, Email: paivi.lampinen@ksshp.fi, Tel.+35814 269 5134, Postal address: Keskussairaalantie 19, rak. 1, Minikampus (2. krs), 40620 Jyväskylä, Finland. For more information about requests related to dataset access, please contact principal investigator, Professor Sarianna Sipilä (sarianna.sipila@jyu.fi), University of Jyväskylä.

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Results

No significant group-by-time interaction was observed for physical activity (p>0.1). The subjects were likely to select an activity category higher than baseline throughout the study (pooled data: B = 0.720–1.614, p<0.001–0.046). Higher baseline Stroop predicted higher physical activity through all subsequent time-points (pooled data: B = 0.011–0.013, p = 0.015–0.030). Higher baseline TMT B–A predicted higher physical activity at 6m (pooled data: B = 0.007, p = 0.006) and during COVID-19 (B = 0.005, p = 0.030). In the PT group, higher baseline Letter Fluency predicted higher physical activity at 12m (B = -0.028, p = 0.030) and follow-up (B = -0.042, p = 0.002).

Conclusions

Cognitive training did not have additive effects over physical training alone on physical activity, but multicomponent training and higher executive function at baseline may support adaptation to and maintenance of a physically active lifestyle among older adults.

Introduction

Physical activity is crucial for older adults' health, functioning and well-being [1, 2]. Despite the well-known and numerous benefits, physical activity declines with increasing age [3] and a large proportion of older adults are physically inactive [4, 5]. Physical inactivity has been considered a severe challenge worldwide and defined as a pandemic for almost ten years ago [6]. Group exercise interventions may be an effective tool to increase older adults' physical activity [1, 7, 8], since they enable e.g., social support, perceived health benefits, feeling better and getting up, out and going [9]. The positive effects of training programs on physical activity tend, however, to be short-lived [7]. Thus, more research is needed on what intervention strategies lead to sustained changes in physical activity.

Among older adults, better executive functions–higher order cognitive processes required for planned and goal-oriented behavior [10]–have been recognized as potential predictors of higher physical activity, exercise adherence and maintenance [11–14]. Current research suggests that fundamental facets of executive functioning, including working memory, behavioral inhibition and task switching, underlie self-regulation [15]. Executive function may also influence the capability to choose a behavior that may require acute exertion and discomfort but bring benefits in the long term, instead of a behavior that brings acute pleasure but is associated with negative long-term consequences [16].

A large body of research suggests that both physical [17, 18] and cognitive training interventions can improve executive function [19]. Furthermore, a recent meta-analysis suggests that combining physical and cognitive training may lead to greater increases in executive functioning than physical training alone [20], and the evidence is complemented by our previous study [21]. In a 12-month randomized controlled trial, we found that some aspects of executive functions improved more in older adults, who participated in targeted executive functions training in addition to physical training compared to those, who were assigned to physical training alone [21]. Even though the transfer effects of executive functions training on everyday life behavior are not clear [22], complementing exercise interventions with executive functions training may improve executive functions and thus facilitate better adherence to a physically active lifestyle. It has, however, not been studied, if targeted executive functions training in addition to physical training can support adherence to a structured physical training intervention or maintenance of physical activity during the post-intervention follow-up period.

Executive functions also facilitate the adaptation to novel and challenging situations [23], and may therefore be of special importance for maintaining physical activity in situations, where habitual physical activity and exercise routines are challenged. Currently, the world is facing the Coronavirus Disease 2019 (COVID-19) pandemic, and concerns have arisen that it may lead to worsening of the physical inactivity pandemic [24]. During the outbreak of the COVID-19 in the spring 2020, all public sports facilities were closed, group activities quitted, and gatherings of more than ten people were prohibited in Finland. Furthermore, people over 70 years were obligated to stay in self-quarantine and to avoid physical contacts with others. In these exceptional circumstances, a person with higher executive functions may find new ways to be physically active. In a recent study, executive functioning deficits were associated with negative changes in physical activity during COVID-19 among younger adults [25], but research is lacking among older adults.

This is an exploratory post-hoc analysis of the PASSWORD-study, a 12-month randomized controlled trial with a one-year post-intervention follow-up [21, 26]. In the study, some aspects of executive functions improved more among older adults participating in physical and cognitive training intervention compared to those attending physical training alone, but gait improved similarly in both study groups [21]. The present study includes also an extended follow-up during COVID-19 lockdown, which was declared in mid-March 2020, when the original 12-month follow-up period of the PASSWORD-study was about to end.

The aim of this study was to investigate, whether 12-months physical and cognitive training intervention had greater effects than physical training alone on physical activity among older adults, who did not meet physical activity recommendations prior to the intervention. We hypothesized that physical activity improved more and was maintained better after the interventions, when continuous supervision and support from the study personnel were ended, in the combined training group. Additionally, we investigated if executive functioning was associated with physical activity during the interventions, follow-up, and the COVID-19 pandemic. We hypothesized that higher executive function predicted higher physical activity.

Methods

Study design

This is an exploratory post-hoc analysis of the PASSWORD-study ("Promoting safe walking among older people", ISRCTN52388040), a two-arm, parallel-group, single-blinded randomized controlled trial conducted at the Gerontology Research Centre at the Faculty of Sport and Health Sciences, University of Jyväskylä, Finland [21, 26]. The study had a one-year post-intervention follow-up, and the present analysis also includes an extended follow-up during COVID-19 lockdown. During the post-intervention measurements, participants were encouraged to continue a physically active lifestyle and received information about senior gyms and training groups in the city of Jyväskylä. Other support or supervision was not provided by the study personnel after the intervention.

The main outcome of the PASSWORD was 10 meters maximal walking speed. Study design and recruitment process have been described in detail [26] and main results have been published [21]. Sample size calculations were performed a-priori for the main outcome of the PASSWORD-study, i.e., 10 meters maximal gait speed, as reported by Sipilä et al [21, 26]. A priori power analysis was not conducted for this exploratory study.

The reporting of this trial followed the Consolidated Standards of Reporting Trial guidelines (CONSORT; S1 File). This study has been carried out in accordance with Declaration of Helsinki and the study protocol was approved by the Ethics committee of the Central Finland Health Care District (14/12/2016, ref: 11/2016; 24/4/2020, ref: 11U/2016). All participants signed a written informed consent before baseline measurements. The trial protocol, including analysis plans for the primary outcome measure, was prospectively registered on the ISRCTN registry (52388040). The original research plan for the PASSWORD-study is provided as S2 File. Major changes considering the present study were exclusion of three months measurements due to lack of resources and addition of the COVID-19 questionnaire. These changes were approved by the ethics committee.

Participants

Community-dwelling, 70–85 years old men and women, who lived in the city of Jyväskylä, Finland, were recruited between January 2017 and March 2018. Participants were eligible for the study, if they did not meet the physical activity recommendations of the time (less than 150 min of moderate activity/week and no regular resistance training), were able to walk 500 m without assistance, and scored $\geq$ 24 points in the Mini Mental State Examination (MMSE) test. Exclusion criteria were: severe chronic condition and/or medication or behavioral factor that could have compromised participation in the study, difficulties in communication due to severe vision or hearing problem, excessive alcohol consumption, and other family member participating in the PASSWORD-study. An initial random sample of 3862 people was drawn from the Finnish National Population Registry. After a screening interview over phone and clinical screening of the inclusion and exclusion criteria at the laboratory, 314 participants were recruited to the study (Fig 1).

Randomization and blinding

Participants were randomized in a 1:1 ratio to receive either physical and cognitive training (PTCT, n = 155) or physical training alone (PT, n = 159). A computer-generated random allocation sequence, created by a senior biostatistician, was used to allocate subjects into training groups in randomly varying blocks of two and four, stratified by sex and age group (70–74, 75–79, 80–85). Randomization and assigning participants to intervention was done by a senior researcher, who did not participate in the data collection or the interventions. Investigators collecting the data and supervisors of physical training groups were blinded to the group allocation, and participants were asked not to mention their group to the investigators or supervisors.

Interventions

Interventions have been described in detail in previous publications [21, 26]. Briefly, both study groups participated in a multicomponent physical training program. The intervention was adapted from the physical activity recommendations for older adults of the time [27], our earlier study [28], and the LIFE-study [29, 30]. Physical training was divided into several training periods, which varied in terms of training specificity, volume and intensity. Training loads and difficulty were increased progressively. Two supervised 45–60 minutes training sessions per week were organized: one concentrating on walking and dynamic balance and the other on resistance and balance training. Supervised walking sessions consisted of a warm-up, including walking at self-selected speed and progressive dynamic balance exercises, and continuous walking for 10–20 minutes at a target intensity of 13–15 on the Borg scale [31]. The resistance exercise sessions started with a 10-minute warm-up and balance exercises.

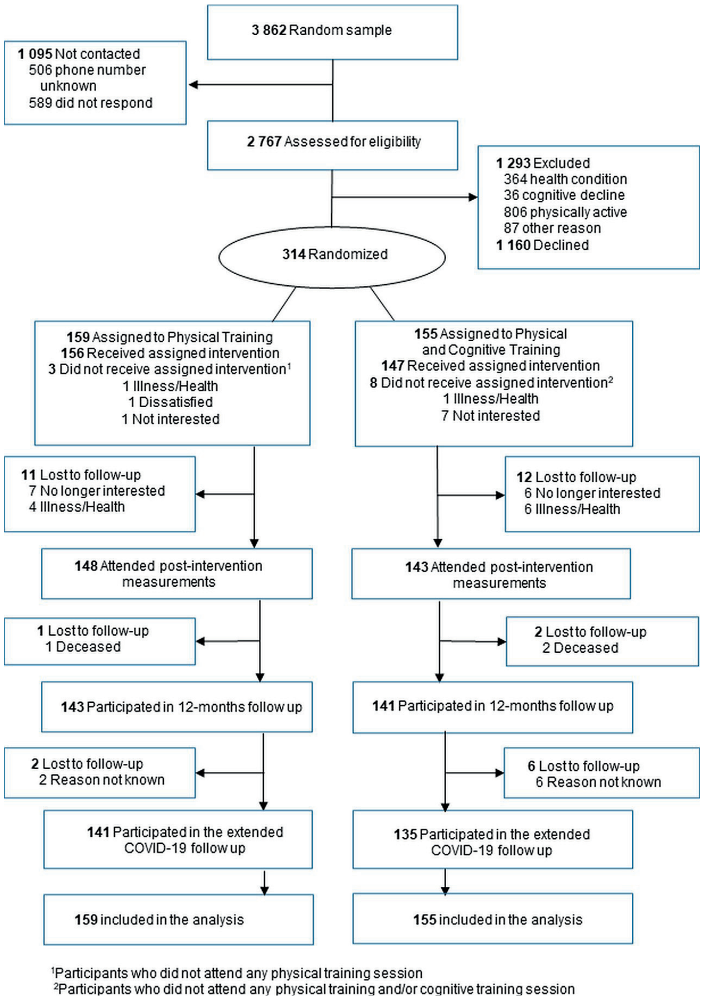

Fig 1. Flow chart of the study.

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Thereafter, 8–9 resistance exercises targeting lower body, trunk and upper body muscles were performed with machines utilizing air pressure technology (http://www.hur.fi/en). Participants received also a progressive home exercise program with target training frequency of 2–3 times per week, including strengthening exercises for the lower limbs, balance training and stretching. In addition, participants were instructed to accumulate 150 minutes per week of moderate intensity aerobic activity in bouts of at least 10 minutes. Physical training sessions were supervised by trained research assistants, who were Master's degree students of sport and health sciences or physiotherapist students. The average duration of the intervention was 51 weeks and on average 46 supervised resistance training sessions were provided. Walking exercises were started after adoption phase to physical training and had a summer break, resulting in an average of 36 supervised walking sessions provided.

The cognitive training (CT) was performed on an in-house developed web-based computer program (iPASS), which was modified from a program previously used in other studies [32, 33]. CT was started at a university computer class, and supervised by trained research assistants with, at least, psychology as a minor subject. CT targeted executive functions, i.e., inhibition, shifting and updating of working memory. Four different tasks were practiced during each training session. The tasks were organized into two blocks: Block 1 included letter updating, predictable set-shifting, spatial working memory maintenance, and color inference tasks to train inhibition, whereas Block 2 included spatial updating, unpredictable set-shifting, spatial working memory maintenance, and number inference tasks to train inhibition. Target training frequency was 3–4 times a week. Participants were allowed to start CT at home after 2–3 group sessions, if they had a computer and necessary computer skills. Participants were also given the possibility to train at the University computer class and/or specific locations provided by the City of Jyväskylä. Support for computer skills was available during given training times at the university and other specific locations. The first weeks of the intervention consisted of an adoption phase to physical training, and the average length of the cognitive intervention was 46 weeks.

Adherence and adverse events have been reported previously, and no between-group differences were observed [21]. As reported earlier by Sipilä et al [21], approximately 40% of the participants reported some adverse events, and 10% reported intervention-related adverse events or symptoms. These were mostly transient non-severe pain and/or discomfort in the joints and/or muscles of the lower body.

Outcome measures

Physical activity. Physical activity was assessed with a questionnaire at baseline (BL), after six (6m) and twelve months (12m) of the interventions, one-year post-intervention follow-up (FU) and during the COVID-19lockdown. The time from FU to COVID-19 varied between two weeks and sixteen months (median six months) depending on the recruitment date of the participant. A single-item, seven-option response scale question about the current physical activity participation was utilized ("Which of the following descriptions best corresponds to your physical activity at the moment?"). The response options were: (0) I do not move more than is necessary in my daily chores, (1) I go for casual walks and engage in light outdoor recreation 1–2 times a week, (2) I go for casual walks and engage in light outdoor recreation several times a week, (3) I engage 1–2 times a week in brisk physical activity (e.g. yard work, walking, cycling) to the point of perspiring and some degree of breathlessness, (4) I engage several times a week (3–5) in brisk physical activity (e.g. yard work, walking, cycling) to the point of perspiring and some degree of breathlessness, (5) I do keep-fit exercises several times a week in a way that causes rather strong shortness of breath and sweating during the activity, and (6) I participate in competitive sports and maintain my fitness through regular training [34]. Participants were asked to select the highest response option that corresponded to their current physical activity. Due to no responses in category 6 and very few responses in category 5, categories 4 and 5 were combined for the analyses.

At BL, 6m and 12m participants returned the questionnaire at the research center during the laboratory assessments. FU questionnaire was posted to each participant with a prepaid envelope one year after his/her post-intervention measurement and returned by mail. Reminder calls were made, if necessary. If a participant returned the questionnaire with missing data, it was completed interviewer-assisted over telephone. Data collection was completed in April 2020. COVID-19 questionnaire was sent with a prepaid return envelope in the end of April 2020. A reminder text message was sent approximately a month later and a reminder and a new questionnaire with a new prepaid envelope were posted in beginning of June, if necessary. At that time point, the state of emergency was still in force and people aged over 70 years were recommended to self-quarantine, even though the institutional services were reopening. Data collection was completed in the end of June 2020. Timeline of the study is shown in Fig 2.

The questionnaire used in this study has acceptable test-retest reliability but limited validity among middle-aged women [35]. This kind of a single-item questionnaire can be sensitive enough to detect statistically significant group-by-time interactions in change of physical activity due to a physical training program [36].

Executive functions. Executive functions were assessed at baseline, and after six and twelve months of the interventions with Color-Word Stroop Test (Stroop) [37], Trail Making Test B–A (TMT B–A) [38] and Letter Verbal Fluency Test [39]. Stroop was used to assess response inhibition [40]. First, participants were asked to read aloud 72 color words printed in black ink (control). Second, they were asked to read aloud the color of 72 printed X's (congruent). Third, participants were shown a list with 72 color words printed in incongruent color (e.g., the word BLUE printed with red ink) and asked to read aloud the ink color while ignoring the word itself (incongruent). The time to complete each test condition was recorded, and the time difference between the congruent and incongruent conditions was calculated. The smaller the difference, the better the performance.

TMT B–A was utilized to assess cognitive flexibility and set shifting [40]. In TMT A participants were asked to draw a line connecting numbers 1–25 in sequential order, and in TMT B to draw a line connecting alternately numbers 1–13 and letters A–L in ascending order, i.e., from 1 to A, A to 2, 2 to B etc. TMT B–A was calculated as the time difference between completing TMT A and TMT B, smaller difference indicating better performance.

Letter fluency was utilized to assess updating [41]. Participants were asked to verbally generate as many unique words beginning with the letters P, A and S as possible in three separate one-minute trials. A sum score of the three trials was calculated. Higher score indicates better performance.

Background characteristics. Sex and age at baseline were drawn from national population registry. Weight (kg) and height (m) were measured by the study nurse, and body mass index (BMI, kg/m^2) was calculated. Fat percent was assessed with dual-energy X-ray absorptiometry (DXA, LUNAR Prodigy, GE Healthcare).

Highest education (college/university degree vs. no college/university degree), marital status (married/cohabiting vs. unmarried/widowed/in a relationship, but not living together), smoking status (never, i.e. smoked less than 100 cigarettes during lifetime, vs. former vs. current), self-perceived current health (very good/good vs. average/poor), perceived difficulties in outdoor mobility (five-scale range from no difficulties to not capable to move outdoors even

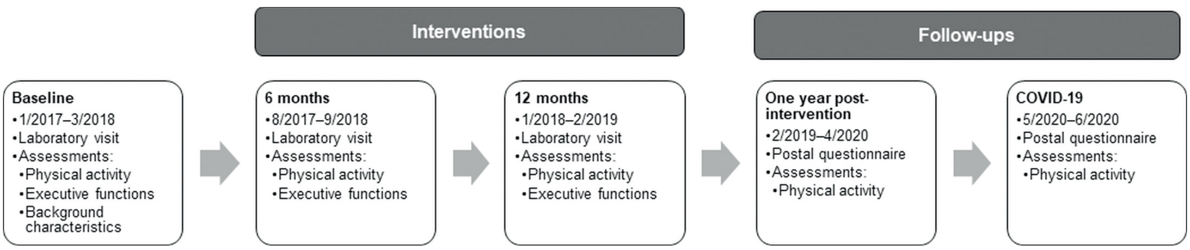

Fig 2. Timeline of the study.

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with assistance, re-categorized as no difficulties vs. at least minor difficulties) and prolonged musculoskeletal pain in any part of the body hindering physical activity (no vs. yes) were drawn from a comprehensive questionnaire. Physical function was assessed with Short Physical Performance Battery (SPPB, total score range 0–12, higher score indicates better performance), including five-time chair rise, habitual walking speed over four meters and standing balance tests [42].

Statistical analysis

Descriptive statistics are shown as means and standard deviations (SD) for continuous variables and frequencies (no.) and percentages (%) for categorical analyses. Differences between participants who dropped out and those who did not were assessed with Pearson's Chi squared test or Fisher's exact test for categorical variables and independent samples t-test for continuous variables.

Initially, two multinomial logistic longitudinal path models (MLLPM) were used to model changes in the physical activity outcome: 1) intervention-control two-group model including time (BL, 6m, 12m, FU and COVID-19), and 2) one-group (pooled) model including only time factor. Wald tests were used for comparison of changes in physical activity across intervention groups (main effects of group, time and group × time interaction) following the intention-to-treat principle. Next, we augmented to models with additional change score models for each of the three executive function variables to assess the impact of changes in executive functions on concurrent and subsequent physical activity measurement (Fig 3). These analyzes were conducted separately and joint for the three executive function variables.

In addition to those who dropped out, information on physical activity was missing from one participant at 6m, two participants at 12m and one participant during FU. One participant did not complete the TMT B–A test at BL and 12m. Based on the assumption that incomplete data was generated through the missing-at-random mechanism, we used the maximum likelihood estimator adapted for incomplete data (for details, see Muthén & Muthén, 1998–2004, Appendix 6) [43] in all models.

The time between FU and COVID-19 measurements was calculated from self-reported response dates on the questionnaires. Missing dates were imputed by hand from questionnaire mailing dates. Participants were expected to have answered the questionnaires within two weeks from posting the questionnaires.

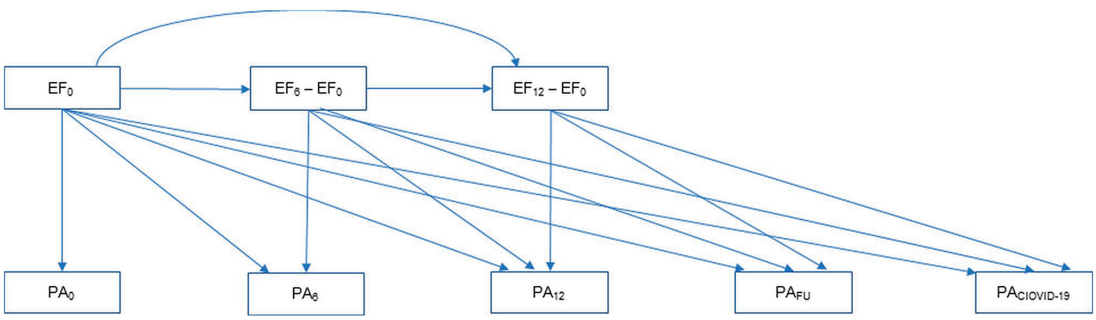

Fig 3. Change score model. Joint and separate change score models were created for the three executive function (EF) variables to assess the impact of changes in executive functions on concurrent and subsequent physical activity (PA) measurement (BL = baseline, 6m = six months, 12m = twelve months, FU = one year post-intervention follow-up).

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Descriptive statistics were computed and attrition analyses performed with IBM SPSS Statistics 26 (SPSS Inc., Armonk, NY). Multinomial logistic models, and joint MLLPM and latent change score models were constructed using Mplus, version 7.4. Statistical significance level was set at 0.05 for all analyses.

Results

Participant characteristics

Participant characteristics (n = 314, mean age 74.5 ± 3.8 years, 60% women) are presented in Table 1. Nearly half of the participants perceived their current health as good or very good at the baseline, but 40% reported prolonged pain hindering physical activity during the past six months, and one of five participants reported at least minor difficulties in outdoor mobility. Mean SPPB score was 10.

Attrition analyses showed that participants who had dropped out at the one year post-intervention follow-up belonged more often to the least physically active category, perceived more often difficulties in outdoor mobility and performed worse in the SPPB test at the baseline than participants who remained in the study (Table 2). Participants who did not participate in the extended follow-up during COVID-19 belonged more often to the least physically active category, were on average older and had lower score in the SPPB test at the baseline than those who remained in the study during all data collecting phases. No statistically significant differences were observed in dropout rates between study groups ($p > 0.68$) or in other background variables ($p > 0.07$).

Changes is physical activity

Changes in distribution of physical activity options selected by the subjects did not differ between the study groups at any measurement time point (Table 3).

At six months, the subjects in both study groups were more likely to select a physical activity category higher than at baseline and the likelihood attenuated only slightly thereafter, but remained on average statistically significantly higher in all time points following baseline (Fig 4 and Table 3). The proportion of participants who selected a physical activity category higher than at baseline was 64% at six months, 53% at twelve months, 46% one year post-intervention and 56% during COVID-19. The proportion of participants belonging to the highest physical activity category, i.e., reporting several times per week brisk activity or keep fit exercise, increased from 13% at baseline to 44% at six months and 37% at twelve months. At the one-year post-intervention follow-up, 29% of participants were in the highest physical activity category, whereas the proportion was 43% during COVID-19.

Executive functions predicting physical activity

The joint effects of baseline performance and subsequent changes in the Stroop, TMT B–A and Letter Fluency tests at baseline on physical activity did not differ between the study groups (p for group × EF interaction = 0.138), but we observed a trend towards statistical significance in pooled data ($p = 0.055$) (Table 4, for details see S1 Table). In separate analysis of each test, the baseline and change effects of Stroop and TMT B–A performance on physical activity did not differ by study group (p for group × EF interaction > 0.3 for both). In the pooled data (one-group model) we found significant associations for Stroop ($p = 0.003$) and TMT B–A ($p = 0.040$) predicting physical activity. As for the Letter Fluency performance, the likelihood ratio test indicted that statistically significant group × EF interactions were observed ($p = 0.026$), suggesting the predictive effect was statistically significant only in the training combination-specific

Table 1. Participant characteristics by physical and cognitive training (PTCT) and physical training (PT) groups.

	PTCT (n = 155)	PT (n = 159)
Age, mean (SD), y	74.4 (3.9)	74.5 (3.8)
Women, no. (%)	96 (62)	92 (58)
Body mass index, mean (SD), kg/m^2	28.0 (4.9)	27.9 (4.5)
Fat percent, mean (SD); n_{PTCT} = 154	36.4 (8.3)	35.9 (8.1)
Marital status, no. (%)		
Cohabiting	102 (66)	97 (61)
Other	53 (34)	62 (39)
Education, no. (%)		
College /university degree	38 (25)	28 (18)
High school or less	117 (76)	131 (82)
Smoking status, no. (%)		
Never smoker	94 (61)	97 (61)
Former smoker	52 (34)	57 (36)
Current smoker	9 (6)	5 (3)
SPPB, mean (SD) [a]	10.2 (1.5)	10.1 (1.6)
Perceived difficulties in outdoor mobility, no. (%)		
No difficulties	122 (79)	123 (77)
At least minor difficulties	33 (21)	36 (23)
Self-rated health, no. (%)		
Very good/good	73 (47)	68 (43)
Average/poor	82 (53)	91 (57)
Prolonged pain hindering physical activity, no. (%) [b]	66 (43)	59 (37)
Stroop difference, s, mean (SD) [c]		
Baseline	45.1 (20.8)	48.1 (28.5)
6 months	34.3 (19.5) (n = 148)	46.5 (25.5) (n = 151)
12 months	34.2 (17.2) (n = 141)	43.6 (20.4) (n = 148)
TMT B-A, s, mean (SD) [d]		
Baseline	87.2 (55.0)	88.9 (49.4) (n = 158)
6 months	76.5 (47.6) (n = 148)	86.8 (41.8) (n = 151)
12 months	76.3 (57.6) (n = 141)	84.1 (49.4) (n = 147)
Letter fluency, no. of words, mean (SD)		
Baseline	42.3 (13.1)	40.9 (12.9)
6 months	43.2 (13.1) (n = 148)	40.9 (12.1) (n = 151)
12 months	46.7 (14.2) (n = 141)	44.3 (13.3) (n = 148)

Note.

[a] Short Physical Performance Battery.

[b] Self-reported, daily or almost daily pain lasting for at least one month during the past six months in neck/shoulders, arms/hands, lower back, hip, knees, or ankles/feet.

[c] Stroop incongruent–Stroop congruent.

[d] Trail Making Test B–Trail Making Test A.

https://doi.org/10.1371/journal.pone.0258559.t001

two-group model. Therefore, for Stroop and TMT B–A, we examined the time point-specific impact of performance on physical activity category probabilities using pooled data, while for Letter Fluency we examined the training groups separately (two-group model).

Baseline performance in any executive functioning test was not associated with baseline physical activity (Table 5). In the pooled data, better baseline Stroop performance predicted

Table 2. Attrition analysis by participants' baseline characteristics.

	One year post-intervention follow-up			COVID-19		
	Respondents (n = 288)	**Non-respondents (n = 26)**	**P**	**Respondents (n = 276)**	**Non-respondents (n = 38)**	**P**
Group, no. (%)			0.685			0.731
PTCT	141 (49)	14 (54)		135 (49)	20 (53)	
PT	147 (51)	12 (46)		141 (51)	18 (47)	
Sex, no. (%)			0.837			1.0
Women	173 (60)	15 (58)		165 (60)	23 (60)	
Men	115 (40)	11 (42)		111 (40)	15 (40)	
Age, yrs, mean (SD)	74.3 (3.8)	75.6 (3.9)	0.114	74.3 (3.8)	75.8 (3.8)	**0.020**
BMI, mean (SD), kg/m^2	27.8 (4.7)	29.4 (4.9)	0.099	27.8 (4.7)	28.9 (4.5)	0.191
Fat percent, mean (SD)	35.9 (8.3)	38.9 (6.7)	0.072	35.9 (8.2)	38.2 (7.9)	0.110
Marital status, no. (%)			0.834			0.722
Married/cohabiting	183 (64)	16 (62)		176 (64)	23 (60)	
Other	105 (36)	10 (38)		100 (36)	15 (40)	
Education, no. (%)			0.453			1.0
College/university degree	59 (20)	7 (27)		58 (21)	8 (21)	
High school or less	229 (80)	19 (73)		218 (79)	30 (79)	
Smoking status, no. (%)			0.934			0.832
Current	13 (4)	1 (4)		13 (5)	1 (3)	
Former	99 (34)	10 (38)		95 (34)	14 (37)	
Never	176 (61)	15 (58)		168 (61)	23 (60)	
SPPB, mean (SD), score [a]	10.2 (10.5)	9.4 (1.9)	**0.006**	10.2 (1.4)	9.5 (2.0)	**0.023**
Difficulties in outdoor mobility, no. (%)			**0.046**			0.144
No difficulties	229 (80)	16 (62)		219 (79)	26 (68)	
At least minor difficulties	59 (20)	10 (38)		57 (21)	12 (32)	
Self-rated health, no. (%)			0.839			1.0
Very good/good	130 (45)	11 (42)		124 (45)	17 (45)	
Average/poor	158 (55)	15 (58)		152 (55)	21 (55)	
Prolonged pain hindering physical activity, no. (%)			0.836			0.860
Yes	174 (60)	15 (58)		167 (60)	22 (58)	
No	114 (40)	11 (42)		109 (40)	16 (42)	
Stroop difference, mean (SD), s	46.7 (24.7)	46.7 (28.3)	1.0	46.9 (25.1)	45.2 (24.4)	0.694
TMT B–A, mean (SD), s	87.4 (51.2)	94.7 (62.9)	0.501	87.3 (51.2)	93.5 (54.8)	0.490
Letter fluency, mean (SD), score	42.0 (13.1)	37.3 (11.6)	0.078	42.0 (13.2)	38.7 (10.9)	0.139
Physical activity category, no. (%)			**0.047**			**0.039**
0	35 (12)	8 (31)		33 (12)	10 (26)	
1	79 (27)	4 (15)		75 (27)	8 (21)	
2	67 (23)	5 (19)		66 (24)	6 (16)	
3	72 (25)	4 (15)		70 (25)	6 (16)	
4/5	35 (12)	5 (19)		32 (12)	8 (21)	

Note.

[a] Short Physical Performance Battery, total score, range 0–12, higher score indicates better performance.

[b] Self-reported, daily or almost daily pain lasting for at least one month during the past six months in neck/shoulders, arms/hands, lower back, hip, knees, or ankles/feet.

[c] Stroop incongruent–Stroop congruent.

[d] Trail Making Test B–Trail Making Test A.

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Table 3. Effect estimates in longitudinal linear multinomial model for changes in physical activity category probabilities over time points.

Effect	Parameterization	Est.	S.E.(Est.)	p
Group	PTCT–PT	-0.08	0.34	0.801
Time	6m –BL	1.61	0.29	<**0.001**
	12m –BL	1.34	0.29	<**0.001**
	FU–BL	0.72	0.30	**0.018**
	COVID-19 –BL	1.50	0.29	<**0.001**
Group×Time	$PTCT_{6m\ -BL}-PT_{6m\ -BL}$	0.16	0.41	0.690
	$PTCT_{12m\ -BL}-PT_{12m\ -BL}$	0.11	0.42	0.791
	$PTCT_{FU-BL}-PT_{FU-BL}$	0.59	0.43	0.171
	$PTCT_{COVID\text{-}19\ -BL}-PT_{COVID\text{-}19\ -BL}$	0.28	0.42	0.502

Note. Physical activity reference category: highest category (Brisk activity or keep fit exercise several times per week). PT = physical training (Ref), PTCP = physical and cognitive training; BL = baseline (Ref); 6m = six months; 12m = twelve months; FU = one-year post-intervention follow-up. Est = regression coefficient estimate, S.E. (Est) = standard error of regression coefficient estimate. Wald test of time: 42.20 (df = 4), $p < 0.0001$; Wald test of time-group interaction: 2.66 (df = 4), $p = 0.6160$.

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likelihood to select higher physical activity response option (i.e. smaller probability to belong to lower physical activity category) in all subsequent time points from six months to COVID-19 (p = 0.015 to 0.030). Better baseline TMT B–A performance predicted the likelihood to select higher physical activity category at six months of the intervention and during COVID-19 (p = 0.006 and p = 0.030, respectively). For Stroop and TMT B–A, changes in executive functions from baseline to six and/or twelve months were not predictive of physical activity at any time point, even though there was a trend towards greater changes in Stroop performance from baseline to six months being predictive of selecting a higher physical activity category at six and twelve months and one year post-intervention (p = 0.087–0.089).

For the Letter Fluency test, statistically significant effects were observed only for the PT group in the two-group model (Table 5). Better baseline performance predicted higher physical activity at twelve months of the interventions and during one-year post-intervention follow-up in the PT only group (p = 0.030 and p = 0.002, respectively). In addition, greater

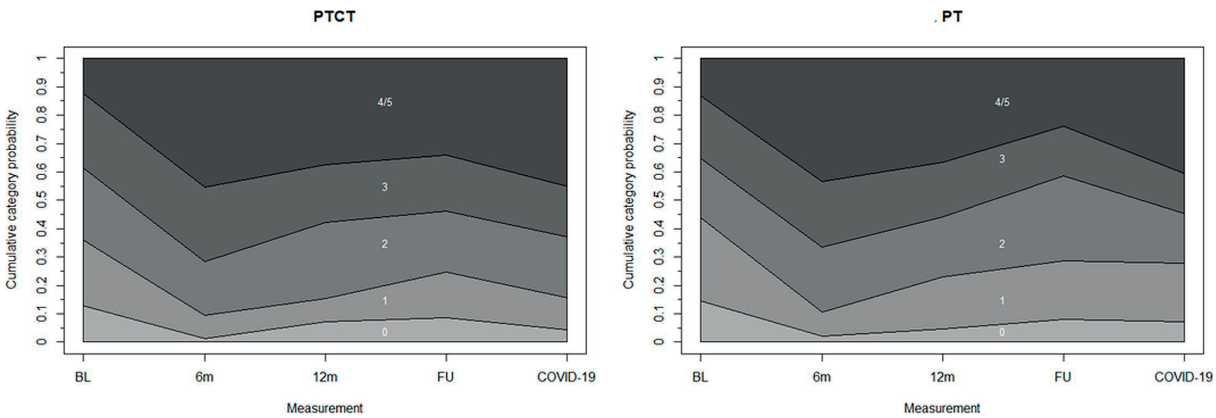

Fig 4. Physical activity category selection probability by study group from the multinomial logistic longitudinal path model. Physical activity categories: 0 = No more than necessary; 1 = Casual walks/light outdoor recreation 1–2 times a week; 2 = Casual walks/light outdoor recreation several times a week; 3 = Brisk physical activity 1–2 times a week; 4/5 = Brisk physical activity or keep fit exercise several times a week. BL = baseline; 6m = six months; 12m = twelve months; FU = one year post-intervention follow-up.

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Table 4. Tests on effect constraints for executive functions on physical activity.

	Two groups						One group		
	EF → PA			EF × group → PA			EF → PA		
	χ^2	df	p	χ^2	df	p	χ^2	df	p
Joint Stroop, TMT, LF	90	72	0.070	45	36	0.138	51	36	0.055
Stroop	38	24	**0.032**	13	12	0.384	30	12	**0.003**
TMT	35	24	0.072	13	12	0.371	22	12	**0.040**
LF	41	24	**0.016**	23	12	**0.026**	20	12	0.064

Note. 'EF → PA' tested if all paths from executive functions to physical activity could be constrained to zero across all time points; 'EF × group → PA' tested equality of all paths from executive functions to physical activity between intervention groups over all time points. Under the heading 'two groups' intervention groups were used in a two-group path model, and under 'one group' data were pooled. $\chi 2$ = Wald chi-square test statistic, df = degrees of freedom. A significant chi-square statistic indicates that the constraint in question would lead to significant worsening of model fit and to oversimplification.

Joint Stroop, TMT, LF: Joint effects of Stroop, TMT B-A and Letter Fluency tests.

Stroop: Stroop incongruent–Stroop congruent.

TMT: Trail Making Test B–Trail Making Test A.

LF: Letter Fluency.

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improvement in the Letter Fluency test performance from baseline to twelve months predicted higher physical activity at twelve months in the PT group (p = 0.020).

Discussion

In this exploratory analysis we found that cognitive training, targeting executive functions, in addition to multicomponent physical training did not lead to greater improvements in self-reported physical activity compared to physical training alone among older adults, who did not meet physical activity recommendations prior to the intervention. In comparison to their baseline physical activity, the participants were likely to select their highest activity category after the first six months of the interventions. Remarkably, in both the one-year post-intervention follow-up and extended follow-up during the COVID-19 restrictions, the participants consistently reported a physical activity category higher than at baseline. Our findings also suggest that higher executive function scores at the baseline may predict better adoption to and maintenance of physical activity due to a multicomponent training intervention.

A recent meta-analysis suggested that combined physical and cognitive training interventions lead to greater improvements in executive functions than physical training alone [20], and our previous study lends support to this finding [21]. Higher executive functioning, in turn, is suggested to support healthy behavior such as physical activity [16]. We therefore expected that combining executive functions training with physical training would increase physical activity more than physical training alone, especially after the interventions when continuous supervision and support from the study personnel were ended. However, we did not observe differences between the study groups. One explanation may be, as suggested by Hall and Marteau [22], that the transfer effects of targeted executive functions training remain ambiguous. Thus, the cognitive training of the present study may not have provided sufficient transferable effects to promote healthier behavior in everyday life over the multicomponent physical training.

Adherence to the physical training program was similar in both study groups [21], and the multimodal physical training program itself may have been effective enough to promote adoption to physically active lifestyle and to overcome the impact from cognitive training. As expected based on previous studies [7], the likelihood to report a high physical activity

Table 5. The effects of executive functioning test performance at baseline and changes in test performance on physical activity from the longitudinal linear path model in full study sample.

	PA_0			PA_6			PA_{12}			PA_{FU}			$PA_{COVID\text{-}19}$		
	Est.	**S.E.**	**p**	**Est.**	**S.E.**	**p**	**Est.**	**S.E.**	**p**	**Est.**	**S.E.**	**p**	**Est.**	**S.E.**	**p**
Pooled data															
Stroop															
$Stroop_0$	0.000	0.004	0.977	0.011	0.005	**0.030**	0.013	0.005	**0.015**	0.013	0.006	**0.022**	0.013	0.006	**0.023**
$Stroop_{6\text{-}0}$				0.011	0.006	0.087	0.012	0.007	0.087	0.012	0.007	0.089	0.010	0.007	0.172
$Stroop_{12\text{-}0}$							0.006	0.008	0.420	0.006	0.008	0.493	0.003	0.009	0.738
TMT															
MT_0	0.001	0.002	0.420	0.007	0.002	**0.006**	0.003	0.002	0.191	0.003	0.002	0.182	0.005	0.002	**0.030**
$TMT_{6\text{-}0}$				0.001	0.003	0.727	-0.002	0.003	0.633	-0.002	0.004	0.621	0.003	0.004	0.385
$TMT_{12\text{-}0}$							-0.001	0.003	0.805	0.003	0.003	0.431	-0.002	0.003	0.599
Two-group model															
LF, PTCT															
LF_0	0.013	0.011	0.211	-0.011	0.012	0.358	-0.005	0.012	0.708	0.001	0.012	0.963	-0.009	0.013	0.497
$LF_{6\text{-}0}$				-0.007	0.018	0.699	-0.027	0.020	0.173	-0.022	0.021	0.291	0.001	0.021	0.961
$LF_{12\text{-}0}$							0.015	0.019	0.428	0.010	0.020	0.618	-0.003	0.020	0.874
LF, PT															
LF_0	-0.010	0.010	0.345	-0.019	0.013	0.127	-0.028	0.013	**0.030**	-0.042	0.013	**0.002**	-0.020	0.013	0.126
$LF_{6\text{-}0}$				0.038	0.024	0.111	0.040	0.028	0.148	0.006	0.026	0.826	0.002	0.027	0.946
$LF_{12\text{-}0}$							-0.054	0.023	**0.020**	-0.006	0.022	0.785	0.007	0.023	0.741

Note.

PA_0: Physical activity at baseline.

PA_6: Physical activity at six months of the interventions.

PA_{12}: Physical activity at twelve months of the interventions.

PA_{FU}: Physical activity at one-year follow up.

$PA_{COVID\text{-}19}$: Physical activity during COVID-19 restrictions.

EF_0: Performance in the executive functioning test in question at baseline.

$EF_{6\text{-}0}$: Change in performance in the executive functioning test in question from baseline to six months.

$EF_{12\text{-}0}$: Change in performance in the executive functioning test in question from baseline to twelve months.

Stroop: Stroop incongruent–Stroop congruent.

TMT: Trail Making Test B–Trail Making Test A.

LF: Letter Fluency.

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category was attenuated after the end of the interventions in both study groups. However, it is of importance to note that the selected physical activity category of approximately half of the participants was higher than at baseline during the post-intervention follow-up period. Very few previous studies have reported long-term maintenance of physical activity following exercise interventions among older adults, and in those studies the long-term effects have mostly been small or non-existing [7]. One explanation to the relatively good maintenance of physical activity in the present study may be the multicomponent physical training program, which included not only intense supervised training but also home-based exercise to promote adaption to self-motivated training. In addition, behavior change strategies that have previously been considered effective on increasing physical activity [44] were utilized, including feedback and self-monitoring [21]. These intervention strategies seem to have been relatively successful to promote adoption to and maintenance of physically active lifestyle, even though the positive effects slightly attenuated after the first six months of the intervention.

Interestingly, distribution of responses to the physical activity item during the COVID-19 was comparable to the end of the interventions, i.e., even higher than during the one-year post-intervention follow-up. Most previous studies have shown decreased physical activity during COVID-19 restrictions [45, 46], but some have shown increased exercise frequency [47, 48]. Our study is, however, unique compared to other studies on the topic that have mostly been conducted as cross-sectional online surveys [45]. All participants in the present study had received home-based exercise instructions and elastic resistance bands during the interventions, and were thus used to train at home. This may have helped maintain and even increase physical activity during the lockdown. In Finland, older adults also had many possibilities for physical activity outside their homes during the COVID-19 restrictions. Even though people over 70 years were instructed to self-quarantine, no curfew was imposed. In the study area, walkways are good and the nature is close, which create good opportunities for outdoor recreation. In addition, while public sports facilities were closed and training groups were quitted, many private sports facilities remained open. It is also noteworthy that the COVID-19 questionnaire was conducted during April–June, which is an opportune time for gardening and other outdoor activities that are popular among Finnish older adults. In Finland, incidental exercise, and habitual physical activity, such as taking care of errands by foot, is more common than in many other countries, in which physical activity consists mostly of structured exercise. Therefore, it may have been easier for older adults to maintain physically active during the pandemic in Finland than in many other countries.

Even though complementing physical training with executive functions training did not promote physical activity more than physical training alone, we found that higher baseline executive functions predicted selection of higher physical activity category both during and after the interventions. This is in accordance with the conclusion of Greendale and colleagues [49], who suggested that cognitive functioning may impact physical activity in older age and not vice versa. Our finding also lends support to previous studies, which have indicated that executive functions are positively associated with exercise adherence and physical activity [11, 13, 14]. Interestingly, performance in the three executive functioning tests differed in their capability to predict physical activity. This mirrors the Unity/Diversity model of executive functioning–the facets have something in common, yet something different [40]. This may also explain, why the joint effects of executive functions on predicting physical activity did not quite reach statistical significance, but the effects of separate tests were statistically significant–performances in the three tests may be correlated.

Of the three tests utilized, the Stroop was the best predictor of physical activity. Baseline Stroop performance could predict physical activity throughout the study, and there was also a trend towards greater changes in Stroop performance during the first half of the interventions to predict greater probability to select a higher physical activity category in subsequent measurements. This is reasonable, since this kind of test capitalizes not only on automatic response inhibition, but also on common executive functioning, i.e. the capability to maintain and manage goals and to retrieve and implement the right goals at the right time [40]. Especially during such exceptional circumstances as the COVID-19 pandemic, different kinds of goal-setting and goal-oriented behavior are required to independently engage in a physically active lifestyle than to follow a structured and supervised exercise program.

In contrast, the TMT B–A test capitalizes on the shifting facet of executive functioning, which is characterized by requirement of rapid switching between goals [40] and may thus be more essential for adapting to novel situations than for long-term maintenance of physically active lifestyle. It is therefore understandable, that TMT B–A performance may have reflected on physical activity participation at the beginning of the interventions and during the COVID-19, when rapid adaptation to new ways to act was required. Interestingly, better performance in the Letter Fluency test, which is a measure of working memory updating [40, 41], predicted higher physical activity only in the physical training alone group. It may be that the cognitive training in addition to physical training challenged working memory more than physical training alone, and thus the baseline Letter Fluency performance had less predictive effect in the combined training group, even though no between-group differences were observed in test performance [21].

All in all, our findings support the previous evidence that has suggested a positive, bidirectional relationship between executive functions and physical activity, but more research is required on the topic. Future research is needed in more diverse study populations to confirm our findings, and with larger sample sizes to investigate the joint effects of executive functions on physical activity. The initial physical activity category selected by our participants was relatively homogenous in accordance with the aims of the PASSWORD-study, which may be one reason to why we did not observe any associations between executive functions and baseline physical activity. More research is thus required to investigate if executive functions play a role in adoption to physical activity among e.g., more active older adults and those who have contraindications to intense exercising. Investigating the joint effect of executive functions on adoption to and maintenance of a physically active lifestyle in a larger sample would be important to reach sufficient statistical power. It would also be fruitful to investigate, if simultaneous training of executive functions and physical exercise, i.e., doing both during the same session, would promote physical activity more than physical training alone, as recent meta-analyses suggest that simultaneous training has greater effects on cognition than doing cognitive and physical training separately [20, 50].

Limitations

This study has several limitations. First of all, this study was an exploratory post-hoc analysis of a randomized controlled trial. Thus, power consideration was not extended to the outcomes of the present study. Exploratory analyses are hypothesis generating in nature, which in the present study denotes that the goals of the study were generated, and analysis plan designed after the data collection according to the original research plan of the PASSWORD-study was almost finalized, and an additional data collection was conducted during the COVID-19 pandemic. Additionally, the endpoint (i.e., self-reported physical activity) was re-categorized after inspecting the data. For these issues, a minimally adequate sample size was not possible to be determined by conducting a power analysis. However, the exploratory approach can be considered as a strength in the present study since majority of COVID-19 related research is cross-sectional and thus lacking comparison data from the time before the pandemic.

Second, physical activity was measured using a single self-report questionnaire item. Self-reports are based on questionnaire items with a limited range of options, which restricts response information content and, hence, power, with an impact on the ability to detect associations. Also, it is difficult to assess inter-subject comparability of activity category selection, i.e., whether the participants perceive the response options to be equidistant and if the options represent the same kind of real-life activity participation. Device-based measurement of physical activity or a more detailed physical activity questionnaire could have provided activity data with a wider range of variability, but such activity measurement tends to have low repeatability. Self-reported activity level tends to vary less in repeated measurements and may, thus, yield more stable estimates of long-term activity than highly varying device-based assessments. Additionally, attrition analyses showed that participants who dropped out were slightly older, less active, and less fit than participants who remained in the study. It may thus be that the proportion of subjects choosing high physical activity categories during and after the interventions give an over-optimistic picture of the development of physical activity participation. However, drop-out rate was relatively low throughout the measurement time points. Finally, the results of this study are not likely to be generalizable to those older adults, who were not eligible for the present study. We do not, for example, know if older adults with cognitive decline or disabled physical function would benefit from a multimodal training program. Furthermore, differences in exercise and physical activity culture may restrict generalizability of the results outside Finland.

Conclusions

Cognitive training targeting executive functions in addition to a yearlong physical training did not lead to greater increase in physical activity than physical training alone among relatively healthy older adults, who did not meet physical activity recommendations prior to the study. Participants in both study groups were likely to report higher physical activity through all subsequent measurements from six months of the interventions to the time of COVID-19 lockdown than at baseline. It may be that the intensive yearlong multimodal physical training program, including not only supervised but also home-based exercise, was effective enough to support adaptation to a physically active lifestyle. Higher baseline executive functions predicted higher physical activity during and after the interventions, even though the predictive effect varied somewhat according to the test utilized and, for letter fluency, according to the study group. Promoting executive functions may be one additional valuable tool in fighting against physical inactivity pandemic among older adults.

Supporting information

S1 File. CONSORT checklist.
(PDF)

S2 File. Research plan.
(PDF)

S1 Table. The joint effects of executive functions on physical activity in pooled data.
(PDF)

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