Physical activity related digital healthcare

Planning interventions for older people on the example of people with dementia in nursing homes

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Physical activity related digital healthcare: Planning interventions for older people on the example of people with dementia in nursing homes

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For Marc

and our wonderful children

Luis, Hanna, and Pia

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Abbreviations

AD	Alzheimer's Disease
ADL	activities of daily living
AR	augmented reality
App	application
BCT	behavior change techniques
BIT	behavior intention technology
IMF	Intervention Mapping Framework´
InCoPE	individualized cognitive and physical exercise
MCI	Mild Cognitive Impairment
ML	Machine Learning
NHE	nursing home employees
PA	physical activity
PwD	people with dementia
RCT	randomized controlled trial
UX	user experience
VR	virtual reality

Quote

"If we could give every individual the right amount of nourishment and exercise, not too little and not too much, we would have found the safest way to health."

Hippocrates of Kos c.460–c.370 BC

Research Articles

This cumulative habilitation is based on the listed research articles in renowned international (peer-reviewed) journals with an impact in the field of digitalization, geriatrics, dementia, and geriatric physical therapy.

List of international research articles covered by this Habilitation

Research article 1

Barisch-Fritz, B., Trautwein, S., Scharpf, A., Krell-Roesch, J., Woll, A. (2022). Effects of a 16-week multimodal exercise program on physical performance in individuals with dementia: A multicenter randomized controlled trial. Journal of Geriatric Physical Therapy, 45 (1), 3–24. doi: 10.1519/JPT.0000000000000308.

Research article 2

Barisch-Fritz, B., Shah, J., Krafft, J., Geda, Y.E., Wu, T., Woll, A., Krell-Rösch, J. (2025). Physical activity and the outcome of cognitive trajectory: a machine learning approach. Eur Rev Aging Phys Act 22, 1 (2025). doi: 10.1186/s11556-024-00367-2.

Research article 3

Barisch-Fritz, B., Woll., Mechling, H., Krell-Rösch, J. (accepted). Motorische Entwicklung und Mobilität im höheren Erwachsenenalter. In Niessner, Bös & Conzelmann (Hrsg.), Handbuch Motorische Entwicklung.

Research article 4

Trautwein, S., Maurus, P., **Barisch-Fritz, B.**, Hadzic, A., Woll, A. (2019). Recommended motor assessments based on psychometric properties in individuals with dementia: A systematic review. European Review of Aging and Physical Activity, 3(16), 20. doi: 10.1186/s11556-019-0228-z.

Research article 5

Barisch-Fritz, B., Krafft, J., Krell-Rösch, J., Woll, A. (2025). Dementia-specific adaptations to physical performance tests of balance, mobility, and lower limb strength and function: A reliability study in people with dementia. BMC Geriatrics, 25 (1), 908. doi: 10.1186/s12877-025-06710-1.

Research article 6

Barisch-Fritz, B., Bezold. J, Scharpf, A., Trautwein, S., Krell-Roesch, J., Woll A. (2023). A new approach to individualize physical activity interventions for individuals with dementia: Cluster analysis based on physical and cognitive performance. Journal of Geriatric Physical Therapy, 47(3), 145-154. doi: 10.1519/JPT.0000000000000396.

Research article 7

Barisch-Fritz, B., Barisch, M., Trautwein, S., Scharpf, A., Bezold, J., Woll, A. (2020). Designing a mobile app for treating individuals with dementia: Combining UX research with sports science. In: Lames, M., Danilov, A., Timme, E., Vassilevski, Y. (eds.) Full manuscript in Proceedings of the 12th International Symposium on Computer Science in Sport (IACSS 2019). IACSS 2019. Advances in Intelligent Systems and Computing, vol 1028. Springer, Cham. doi: 10.1007/978-3-030-35048-2_22.

Research article 8

Barisch-Fritz, B., Krafft, J., Rayling, S., Diener, J., Krell-Rösch, J., Möller, T., Wunsch, K., Sartorius, M., Riedel, N., Ferreira Maia, M.J., Weinberger, N., von Both, P., Asfour, T., Woll, A. (2023). Are nursing home employees ready for the technical evolution? German-wide survey on the status quo of affinity for technology and technology interaction. Digital Health. 21(9), 20552076231218812. doi: 10.1177/20552076231218812.

Research article 9

Barisch-Fritz, B., Nigg, C., Barisch, M., Woll, A. (2022). App development in a sports science setting. Systematic review and lessons learned from an exemplary setting to generate recommendations for the app development process. Frontiers in Sports and active living, 4(4), 1012239. doi: 10.3389/fspor.2022.1012239.

Research article 10

Barisch-Fritz, B., Bezold, J., Scharpf, A., Trautwein, S., Krell-Rösch, J., Woll, A. (2022b). Usability and effectiveness of an individualized, tablet-Based, multidomain exercise program for people with dementia delivered by nursing assistants: Protocol for an evaluation of the InCoPE-App. JMIR Research Protocols, 11(9), e36247. doi: 10.2196/36247.

Research article 11

Krafft, J., **Barisch-Fritz, B.**, Krell-Rösch, J., Trautwein, S., Scharpf, A., Woll, A. (2023). A tablet-based app to support nursing home staff in delivering an individualized cognitive and physical exercise program for individuals with dementia: Mixed methods usability study. JMIR aging, 22(6), e46480. doi: 10.2196/46480.

Research article 12

Barisch-Fritz, B., Bezold, J., Scharpf, A., Trautwein, S., Krell-Rösch, J., Woll, A. (2022a). ICT-Based individualized training of institutionalized individuals with dementia. Evaluation of usability and trends towards effectiveness of the InCoPE-App. Frontiers in Physiology, 8(13), 921105. doi: 10.3389/fphys.2022.921105.

Research article 13

Prinz, A., Buerger, D., Krafft, J., Bergmann, M., Woll, A., Witte, K.*, **Barisch-Fritz, B.*** (2024). Use of immersive virtual reality in nursing homes for people with dementia: Feasibility study to assess cognitive, motor, and emotional responses. JMIR XR Spatial Comput 1(1), e54724. doi: 10.2196/54724. *equal contribution

Research article 14

Möller, T., Beyerlein, M., Herzog, M., **Barisch-Fritz, B.**, Marquardt, C., Dezman, M., Asfour, T., Woll, A., Stein, T., Krell-Rösch, J. (2025). Human motor performance assessment with lower limb exoskeletons as a potential strategy to support healthy aging-a perspective article. Prog Biomed Eng (Bristol). 2025 Jan 8;7(1). doi: 10.1088/2516-1091/ada333.

1 Introduction

The introduction of this habilitation thesis is divided into two chapters. Chapter 1.1 provides an overview of aging and the associated societal and individual challenges, particularly in relation to the neurodegenerative disease dementia. It explains the motivation for studying physical activity (PA) as a countermeasure to age- and disease-related declines in physical and cognitive performance and highlights the potential of digital exercise interventions. Chapter 1.2 outlines the overall structure of the habilitation thesis.

1.1 Motivation and background

The increase in the life expectancy of the world's population is being driven by a variety of factors, including better access to healthcare, treatment and rehabilitation, higher standards of living and education, changes in the nature and patterns of work, and improved economic and social status of older people (European Commission, 2020; Gerland et al., 2022; OECD, 2017; United Nations, 2019). Today, one in ten people worldwide is over the age of 65 (771 million in total). By 2050, it is estimated that one in six people (1.6 billion) will be over 65, and the number of people over 80 will have tripled by then (Gerland et al., 2022; United Nations, 2019). With increasing age, the likelihood of developing disease increases, as evidenced by the incidence of conditions such as arthritis, osteoporosis, cardiovascular disease, Parkinson's disease and in particular dementia. The strongest risk factor for developing dementia is age itself, thus an aging society will inevitably face higher incidence rates (Westphal & Doblhammer, 2018). Worldwide, 55 million people were affected by dementia in 2019, and this number is expected to rise to 135 million by 2050 (Long et al., 2023).

Symptoms of the neurodegenerative disorder dementia, which is an umbrella term, include a decline in cognitive (WHO, 2019) but also physical function (Beauchet et al., 2008). With the onset of dementia, the disease-related decline is added to the already known age-related decline in cognitive (Harada et al., 2013; Novotný et al., 2022) and physical performance (Buchman et al., 2007; Tittlbach et al., 2017; Vandervoort, 2002). The sum of age- and disease-related limitations leads to an increase in disability and dependency, and thus to a reduction in quality of life (Butterly et al., 2023; Dewilde et al., 2019; Mutubuki et al., 2020).

There is still no cure for dementia, which means that treatment is mainly based on allevating symptoms, with medications often associated with negative side effects (Sink et al., 2005). Non-pharmacological treatment is therefore crucial (Bessey & Walaszek, 2019), and exercise interventions in particular have shown promising effects in maintaining cognitive and

physical function or slowing down disease-related decline (Farina et al., 2014; S. Zhou et al., 2022). Quality of life has been identified by PwD, their families and nursing home emplyoees (NHE) as an important goal of treatment (Logsdon et al., 2007). Factors that have been identified as contributing to the quality of life include mood, engagement in pleasurable activities, and the ability to perform activities of daily living (ADL) (Logsdon et al., 2007). Quality of life and the ability to perform ADL are positively influenced by PA interventions (Liang et al., 2022; S. Zhou et al., 2022). However, the evidence on the effects of PA on dementia symptoms is still inconclusive. This is partly due to the high heterogeneity of people with dementia (PwD) (Potter et al., 2011), but also to the low level of individualization of non-pharmacological treatments (Scales et al., 2018).

Age- and disease-related physical and cognitive decline, as well as the entity and progression of dementia vary widely, so there is great heterogeneity among PwD. The plasticity of the age-related decline can be used to explain some of the variance, but also to explain the counteracting effects of PA. PA, defined as any physical movement produced by skeletal muscles that requires energy expenditure (Bull et al., 2020), is an important factor influencing aging and the onset and progression of disease, and thus contributes to maintaining independent and safe performance of ADL (Bull et al., 2020; Cleven et al., 2020). Buchman and colleagues (Buchman et al., 2007) found that each additional hour of exercise per week was associated with a 5 % reduction in the rate of physical decline, and it has been shown to delay or slow down cognitive decline in older age (Krell-Roesch et al., 2021; Reas et al., 2019).

In general, the influences on potential longevity are numerous, so the concept of plasticity needs to be extrapolated to different socioeconomic or resource settings (Hanson et al., 2016). As PA is a major contributor and the ability to adapt to physical stimuli is maintained at all ages, even in the presence of disease, PA needs to be extrapolated in a similar way. The practice of PA and PA itself is closely linked to psychosocial and demographic factors, as well as the built, social, technological, and natural environment. All of these are important factors that influence physical changes in old age (Schlicht et al., 2016). Consequently, the development of PA and exercise interventions is a complex endeavor, starting with the right training content with appropriate intensities and other control variables, through to the integration into a socioeconomic setting, considering psychosocial and demographic factors that decisively influence the implementation and maintenance of an intervention. The development of public health interventions is largely based on social and behavioral theories. It is generally accepted that interventions developed with an explicit theoretical basis are more effective than those without, and that some strategies that combine multiple theories and concepts are more effective (Glanz & Bishop, 2010; Gourlan et al., 2016). Combining and applying multiple theories and methods and integrating implementation and evaluation planning, is part of the Intervention Mapping Framework (IMF). This framework provides a comprehensive

approach to planning theory and evidence-based interventions, including steps such as needs assessment, program design and implementation (Bartholomew Eldredge et al., 2016).

Digitalization, as the use and interconnection of data and digital technologies leading to new or changed activities, has already found its way into the healthcare including nursing homes. So-called eHealth or mHealth applications are seen as a potential solution to the growing problems of an aging society, i.e., the increased need for care for older people in the face of a shortage of care providers (Zöllick et al., 2020). In Germany, 796,489 people worked in nursing homes and home care services in 2019, caring for 4.13 million people in need of long-term care (Destatis, 2019). With the growing number of older people, the World Health Organization has stated in 2017 that 40 million new jobs in health and social care and about 18 million additional health workers will be needed worldwide by 2030 to achieve high and effective coverage of the wide range of health services needed (WHO, 2017).

However, the actual use and acceptance of digital and technological solutions and services in the care of older people is hampered by access gaps or limited knowledge, as well as a perceived lack of technology adoption (C. Lee, 2022). It is well known that the adoption of information and communication technologies in healthcare tends to take longer than in other sectors, i.e., due to security concerns (Bronsoler et al., 2022). The impact of digital solutions on clinical outcomes, productivity and the healthcare workforce showed rather modest improvements in clinical outcomes and reductions in healthcare costs, and no impact on productivity (Bronsoler et al., 2022). This suggests that the successful integration of digital solutions in healthcare is subject to many influences and confounding factors. In nursing homes, for example, any successful digital solution should address the needs of the older people, while also considering the specific circumstances and requirements of NHE. In nursing homes in particular, there are multiple barriers including the conditions and resources of a particular nursing home, the attitudes and perspectives of people with decision-making power, the actual NHE, the people being cared for, and possible other determinants (Ko et al., 2018).

Digital solutions for PwD have been used in the past, with applications ranging from diagnostics, such as body-worn sensors to detect early signs of functional decline (Jansen et al., 2022), to monitoring, e.g. to capture electronic health records (Shiells et al., 2020). A recent systematic review examined digital health interventions for people with mild cognitive impairment (MCI) or dementia (Di Lorito et al., 2022). This review examined the evidence for the effectiveness of digital health interventions on physical, cognitive, behavioral, and psychological outcomes and ADL in people with MCI or dementia. The digital interventions showed a moderate effect on cognition and a negative moderate effect on basic ADL, with

the main finding being that the implementation of supervised interventions was associated with the greatest benefit (Di Lorito et al., 2022).

Therefore, the provision of exercise interventions by NHE themselves is of current and future interest. This was also prompted by the COVID-19 pandemic and the resulting restrictions. These restrictions forced changes in daily routines and thus the reduction and cancellation of various activities and treatments, which prevented many residents from being physically active (Frahsa et al., 2020). In general, the proportion of sedentary time, which accounts for up to 90 % of the day in nursing homes (Souto Barreto et al., 2015), can best be reduced through interventions led by NHE and their increased knowledge and expertise in exercise interventions. In particular, there is currently a lack of evidence- and theory-based and scientifically evaluated interventions that can be implemented in nursing homes. Most importantly, the known and researched barriers and determinants to implementing and sustaining PA promotion or exercise interventions in nursing homes, i.e., shortages on human resources (Hirt et al., 2023), point to the potential of digitalization. However, the development of a digital solution for nursing homes also faces the challenges of accessibility, acceptability and sustainability of digital interventions, which must be prerequisites for the development of future successful services (Di Lorito et al., 2022). In particular, the design and development of a digital exercise intervention for PwD in nursing homes must take into account the determinants of the nursing home environment.

1.2 Outline

This habilitation thesis is divided into seven chapters (see Figure 1.1). The introductory Chapter 1 presents the motivation and legitimacy of the research areas of PA and dementia and digitalization, as well as the structure of the habilitation thesis. Chapter 2 covers the theoretical background and current research, including aging, age- and disease-related decline, and the effects of PA and exercise. It also discusses biological aging, challenges of interventions for PwD in nursing homes, and the role of digitalization. Theories and methods for planning exercise interventions and their application to digital intervention design are outlined. Chapter 3 summarizes the research deficits in order to derive the research question and the related research objectives. Chapter 4 details the methodology by applying the IMF and summarizes the methods of the individual research articles. Chapter 5 presents the results of this habilitation thesis, in which the individual research articles are presented according to the evaluation plan including each abstract and contribution to the research areas. Chapter 6 discusses the main findings of the habilitation thesis including a critical consideration of the application of the chosen methodological framework but also possibilities for extending it to digital interventions. The chapter also discusses the limitations of the present work. In

Chapter 7, a conclusion is drawn on the application of the generic methodological framework and the results obtained, taking into account the potential but also the challenges of digital interventions, and also deriving essential knowledge that future students of sports science need to have in order to be able to operate in the market of digital intervention development and thus in the field of digital health.

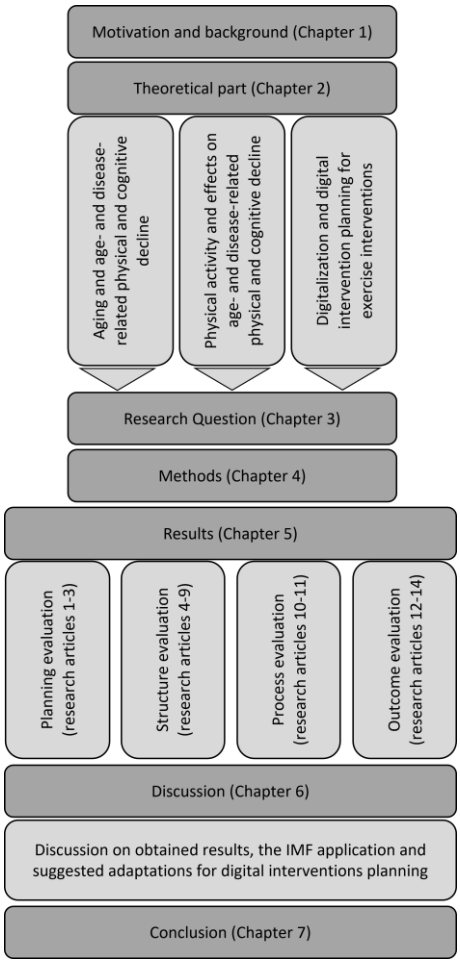

Figure 1.1: Structure of the habilitation thesis

2 Theoretical part

The theoretical part summarizes in three chapters the main contents and interrelations of the three areas of aging, PA, and digitalization relevant to this habilitation thesis. Chapter 2.1 deals with aging and the social relevance of aging. An overview of the models and theories of aging relevant to this habilitation thesis is given. In this context, age-related changes in physical and cognitive performance are described and presented in relation to health-related motor skills. In addition, the disease of dementia and significant disease-related changes in physical and cognitive performance are described. These changes are important for understanding the decline with age and disease, and for assessing opportunities to influence this decline. Chapter 2.2 describes the lifestyle factor of PA and its contribution to cognitive and physical performance in older adults. The chapter begins with a definition and brief overview of PA and the context of health and aging. Based on current research, the effects of PA on physical and cognitive performance in older adults are summarized. The effects of PA in the context of PwD are also presented. Relevant characteristics and challenges of this sample and the nursing home setting are presented in the light of existing studies on the context of PA and the effects of PA in PwD. Chapter 2.3 focuses on digitalization and, in particular, digital exercise interventions. The focus is on the potential of digitalization for the delivery and promotion of PA, particularly in the context of aging. Special emphasis is placed on the planning of exercise interventions, as the lack of a theoretical basis for current digital PA solutions is often criticized. Theories and models related to PA are considered, as well as evidence and theory-based intervention planning. IMF is introduced and its application to exercise intervention planning is explored through a literature review. Each chapter concludes with a brief summary of key messages.

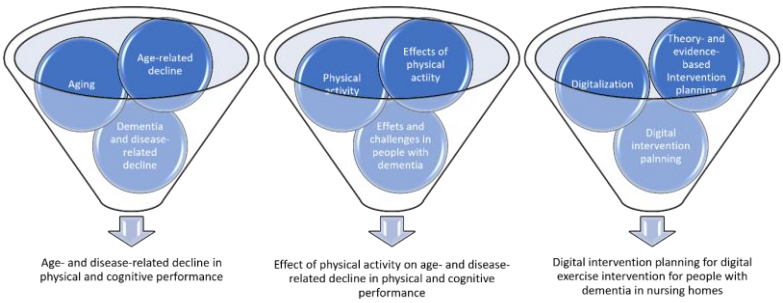

Figure 2.1: Focus of the theoretical part

As shown in Figure 2.1, the theoretical part deals with three main topics, which are covered in the three chapters (Chapters 2.1, 2.2 and 2.3), from the perspectives relevant to the work. In each chapter, it begins broadly, taking into account the wider context, and then focuses on the considerations essential to this work.

2.1 Aging and age- and disease-related physical and cognitive decline

The notion of aging, and healthy aging in particular, has attracted a lot of attention in recent years. The reason for this is the global socio-demographic change caused by lower birth rates combined with advances in medical and pharmaceutical technology, healthcare, and nutrition and hygiene, which is reflected in increasing life expectancy in the statistical records worldwide (European Commission, 2020). Our society is facing major global social, economic and societal challenges resulting from the current prevalence of older people combined with an increase in chronic diseases and age-related limitations in functional, physical and cognitive performance.

This chapter begins with general facts about aging with some definitions and theoretical considerations in Chapter 2.1.1. Chapter 2.1.2 provides an overview of age-related changes in physical and cognitive performance. Chapter 2.1.3 describes the neurodegenerative disorder of dementia with its symptomatic disease-related physical and cognitive decline, with an additional excursus on the measurability of physical performance in PwD. The chapter concludes with a summary of age- and disease-related decline and the associated individual and societal challenges in Chapter 2.1.4.

2.1.1 Aging – facts, definitions and theoretical models

The increase in the life expectancy of the world's population is being driven by a variety of factors, including better access to healthcare, treatment and rehabilitation, higher standards of living and education, changes in the nature and patterns of work, and improved economic and social status of older people (European Commission, 2020; Gerland et al., 2022; OECD, 2017; United Nations, 2019). Today, one in ten people worldwide is over 65 years (a total of 771 million), and it is estimated that by 2050, one in six people (1.6 billion) will be over 65 years, and the number of people over 80 years will have tripled by then (Gerland et al., 2022; United Nations, 2019). These demographic changes of population aging are inevitable in most populations and cannot be stopped in the near future by increased immigration or higher birth rates (Lutz et al., 2003).

Aging can be assigned to the generic term of gerontology. Gerontology, or aging research, is a body of knowledge that deals with all aspects of the aging process, including physical, psychological, social, economic, political and societal aspects, as well as disease-related influences (Willimczik, 2018). Research practice argues that gerontology should be considered as a research program (Willimczik, 2018). Senescence, is a more precise term for aging from a biogerontological perspective, which refers to aging as the progressive deterioration of bodily functions over time associated with a loss of complexity in a variety of physiological processes and anatomical structures (Lipsitz, 2006). Senescence is also used to distinguish physiological aging changes from those that lead to an increased risk of disease, disability or death (da Costa et al., 2016). The disease-related influences and limitations are primarily to be assigned to geriatrics, as a special medical discipline (Willimczik, 2018). In this habilitation thesis, the concept of aging is mainly considered from a biogerontological point of view, but the social significance is also of great relevance within this habilitation thesis.

Aging refers to growing older and is an universal intrinsic and progressive process (Viña et al., 2007). There is no universally accepted definition of the term, nor is there a single classification of the different stages of adult life in terms of years of life. Middle adulthood is often considered to be the period between the ages of 30 and 70 (Mechling, 2017). This phase is followed by older adulthood from 70 to 85 years of age, very old adulthood from about 85 years of age, and extremely old adulthood over 100 years of age (Mechling, 2017). In older age, the content and goals of life change, mostly away from the expansion of tasks, competencies, and resources, which are particularly prominent in early and middle adulthood, towards the maintenance of existing levels of functioning, i.e., independence and coping with everyday life, as well as quality of life (Eichberg & Mechling, 2009). At this older age, life is characterized by changes that affect different areas of life, such as entering retirement, but also physical conditions.

Aging, in its broadest sense, refers to the changes that occur over the lifespan of an organism (da Costa et al., 2016). The onset of the aging process depends on the underlying model or theory and begins either at conception or after the completion of certain maturation processes. However, these changes are highly variable (Kirkwood, 2005) and involve a variety of interactions. Thus, Anton and colleagues (Anton et al., 2005) summarize that the phenotype is the end result of the interaction between genotype and external factors: phenotype = genotype + [diet, lifestyle and environment]. Aging is currently viewed as many processes that combine and interact at many levels (da Costa et al., 2016). The multifaceted and relevant process of aging is the subject of research in many scientific fields. Throughout history, the subject has captivated both scientists and philosophers, so it is not surprising that a variety of theories and models exist.

The categorization of different theories and models of aging is also not uniform. Categorizations vary according to the perspective of the topic, ranging from review articles (Bengtson & Settersten, 2016; Weinert & Timiras, 2003), historical outlines (Agronin, 2014; Birren & Birren, 1990), biochemical theories of aging (Afanas'ev, 2010; Avantaggiato et al., 2015; Freitas & de Magalhães, 2011; Sergiev et al., 2015), to theories with biological (Jin, 2010; G. M. Martin, 2011), and evolutionary backgrounds (Kowald & Kirkwood, 2016; Libertini et al., 2017), transcultural comparisons (Fung & Jiang, 2016; Tesch-Römer & von Kondratowitz, 2006) and psychosocial analyses (Aburn et al., 2016; MacLeod et al., 2016). There is currently no universal classification, but rather a summary of content such as deficit and growth models, activity and attrition theories, and continuity and life course approaches.

The predominantly biochemical models and theories can be broadly categorized as damage or error theories, complex systems approaches, and genetic theories of aging. These theories are constantly evolving and include a variety of studies from genetics, biochemistry, animal models, and longitudinal human studies (A. A. Cohen et al., 2022). Opinions on the description and explanation of the aging process in these different theories are controversial and still ongoing (Blagosklonny, 2013; Goldsmith, 2016). Existing theories are based on different assumptions of molecular cross-linking (Bjorksten, 1968), free radicals causing damage (Harman, 1956), changes in immunological functions (Effros, 2005), telomere shortening (Kruk et al., 1995), the presence of senescence genes in DNA (Gahan, 1988), or a more unified theory that describes the causes of aging through genes, the performance of genetic maintenance and repair systems, the environment, and chance (Rattan, 2006).

From a historical perspective, the move away from purely deficit-oriented models of the aging process can be described by looking at the life-span perspective, which was significantly shaped by Baltes and Baltes (Baltes & Baltes, 1989, 1990). They adopted the concept of "successful aging" from William and Wirths (Williams & Wirths, 1965) and thus provided the basis for the goals of health interventions. The principles of Baltes and Baltes (Baltes & Baltes, 1989) illuminate the aging process from the perspective of the individual and focus on making the aging process as successful as possible for the individual. These guiding principles reflect a number of basic assumptions but do not constitute a comprehensive model. Nevertheless, some of them are central to the present work and continue to provide an essential framework for the design of interventions. They can be summarized as follows: (1) there is a distinction between normal, optimal and pathological aging, (2) the aging process is heterogeneous (variable), (3) there is a considerable "hidden reserve" (plasticity), (4) near the limits of the performance reserve, there is an age-related loss, (5) with increasing age, the balance of developmental gains and losses becomes increasingly negative, (6) the self-image remains intact even in old age (Baltes & Baltes, 1989). Principles one to three are addressed in Chapters 2.1.2 and 2.1.3, while four to six will not be discussed further in this work, as they

are not of primary relevance in view of the sample drawn here, i.e., very old PwD in nursing homes.

Examples of models based on the lifespan perspective are the model of selective optimization with compensation (Baltes & Baltes, 1990; Freund, 2008), the two-process model of developmental regulation (Brandtstädter & Greve, 1994; Brandtstädter & Renner, 1990), the theory of primary and secondary control (Heckhausen & Schulz, 1995), and the model of functional quality of life (M. Martin et al., 2012). Among the many different aspects, the previous approaches have in common that, in addition to age-related changes (losses and gains), they also take into account processes of stabilization and thus include predictors (e.g., individual resources) that shed light on interindividual differences (Mérillat et al., 2018).

Gerontological research currently focuses on chemistry and biochemistry, as these are at the core of aging processes and explain age-related decline. There is currently no integrative model that takes into account all the mechanisms of aging. The prevailing theories of aging therefore include chemical, biological, psychological and pathological aspects. However, the different theories do not satisfactorily explain the aging process (Davidovic et al., 2010). In general, these biological models and theories are important to explain changes in physical performance, which mainly consists of a decline in performance, which is the focus of this habilitation thesis. These theories and models form the basis of the following chapter, which describes the age-related losses in physical and cognitive performance that are primarily based on biochemical processes. The influence of PA as a lifestyle factor on aging, which is the subject of Chapter 2.2, takes more account of the lifespan perspective of the above models and theories.

2.1.2 Age-related physical and cognitive decline

Changes in physical performance, which tends to decline with age, are particularly noticeable and have an impact on the entire living environment. To explain changes in physical performance, it is important to consider motor development as a whole. Motor development is controlled and accompanied by biological, biochemical, and also biomechanical developmental processes. This is most evident in the early stages of life when, for example, longitudinal growth is of particular importance. In old age, physical performance is determined by processes of decline, with neurodegenerative and even pathological processes involved in aging. These can be partly explained by physiological changes such as increased stress levels, mitochondrial dysfunction, inflammatory processes, decreased hormone production and metabolic rates, and generally lead to catabolic and degenerative processes (Cesari et al., 2013; Sieber, 2017). Age-related changes are therefore usually associated with cognitive (Harada

et al., 2013; Novotný et al., 2022) and physical decline (Buchman et al., 2007; Tittlbach et al., 2017; Vandervoort, 2002).

2.1.2.1 Age-related physical decline

Motor development and physical decline generally follow a curvilinear trajectory, beginning with a decline between the ages of 45 and 65, increasing after the age of 65, and accelerating in the last years of life (Conzelmann, 1997; Landré et al., 2021; Wilson et al., 2012; Woll, 2006). Both cognitive and physical decline are facilitated by sensory impairments, such as loss of hearing, vision, smell, and touch (Völter et al., 2021), and age-related changes in personality, emotion, and motivation. These are summarized by the term geronto-psycho-physiology, which describes the indirect or direct influences of multiple processes that alter physical performance in old age (Granacher et al., 2018). At all levels, older adults experience a variety of limitations, e.g., in the area of fine motor skills (Hoogendam et al., 2014; Johannsen et al., 2018), in the execution of bimanual movements (Krehbiel et al., 2017), or in larger motor skills such as walking. These changes have a significant impact on daily life, from participation in leisure activities to ADL and maintaining independence (Ambrose et al., 2013; Ikegami et al., 2019). In addition, age-related changes in motor function are strongly associated with quality of life, increased risk of falls, and mortality rates (Arango-Lopera et al., 2013).

The heterogeneity of the age-related decline is very high and varies between domains of physical and cognitive performance (Olk et al., 2018). Physical decline mainly includes reduced muscle strength and coordination, slowed movements, increased spatial and temporal variability of movements, and impaired postural and gait stability (Seidler et al., 2010). Table 2.1 describes the age-related decline in motor performance based on the motor skills of strength, endurance, balance and flexibility in older adulthood, this summary is based on the book chapter by Barisch-Fritz et al. (Barisch-Fritz et al., accepted). With regard to the relevance of the age-related decline to health, only “health-related” motor skills are considered, i.e., motor speed or reaction time have not been integrated. For the coordinative motor skills, only balance was included as this is an important predictor of falls with age. The summary in Table 2.1 shows the extent of the physical decline, the known causes, and gender and other known influences.

Table 2.1: Age-related physical decline in health-relevant motor skills

Motor skill	Decline rates	Known underlying causes and mechanisms	Influences and dependencies
Strength	• Parabolic course • 1 to 1.5 % per year from age 40 to 50, increasing from age 65 (Goodpaster et al., 2006; Petermann-Rocha et al., 2022) • 2.5 to 3 % in women and 3 to 4 % in men from age 75 (Mitchell et al., 2012)	Loss of muscle mass and function. • Muscle mass decreases due to atrophy and hypoplasia (Wilkinson et al., 2018). Hypoplasia due to denervation, motor unit remodeling (Lexell et al., 1988), and changes in muscle architecture (Narici, 1999; Powell et al., 1984; Strasser et al., 2013; Y.-N. Wu et al., 2016). • Muscle function declines due to neuromuscular changes: i.e., atrophy of type II muscle fibers (Hepple & Rice, 2016; Lexell, 1995), changes in motor units and contractile properties (Connelly et al., 1999), hormonal and metabolic aging changes (Doherty, 2003), and aging processes in the somatosensory system (Edström et al., 2007; Shaffer & Harrison, 2007; Yamada et al., 2019).	• Gender influences in all strength domains with lower strength levels and higher rates of decline in women (Ditroilo et al., 2010; el Hadouchi et al., 2022; Frontera et al., 1991; Macaluso & De Vito, 2004). • Largest age-related decline in muscle power (Dietzel et al., 2013; Tieland et al., 2018; Wiegmann et al., 2021), while muscle mass loss is slower. • Loss of strength is slower in the upper extremities than in the lower extremities (Ditroilo et al., 2010; Frontera et al., 2000).

Motor skill	Decline rates	Known underlying causes and mechanisms	Influences and dependencies
Endurance	• Curvilinear trajectory of maximal endurance performance • 0.5-1 % decline in maximal oxygen uptake (VO2max) per year from age 35 (Malkinson, 2022). • Accelerated decline from age 45 (Jackson et al., 2009), approximately 20 % per decade from age 70 (Fleg et al., 2005). • Results from running competitions suggest relatively small decline until age 50 to 60 and a steeper decline from age 60 (Tanaka & Seals, 2008). • Heart rate variability declines most from age 20 to 40, with a slower decline from age 60 (Frenzl & Schlegel, 2010).	Complex interplay of internal and external factors. • Internal factors: cardiovascular capacity (including cardiac output, heart rate), respiratory capacity (including lung volume, lung perfusion), metabolic capacity (including nutrition, metabolism), muscular capacity (including muscle fiber composition, muscle contraction), hormonal capacity (including hormone concentrations, homeo-regulation of metabolic processes), nervous capacity (including neuronal signals) and mental capacity (Eisenhut & Zintl, 2014; van Beek et al., 2016) • external factors: oxygen partial pressure, climate or different training modes (Eisenhut & Zintl, 2014). • The decline in VO2max with age is mainly due to a reduction in cardiac output, in particular a decrease in maximum heart rate (by about 0.7 beats per minute per year) and stroke volume (by about 80-90 % compared to values of young adults) (Tanaka & Seals, 2008).	• Endurance performance decline is independent of performance level (Donato et al., 2003; Joyner, 1993). • VO2max varies by age and sex, with women averaging 10-15 % lower (Conzelmann & Blank, 2009; Hollmann & Strüder, 2009). • No gender differences in age-related decline of VO2max or heart rate variability. • Influence of training on performance decline is lower in women, possibly due to hormonal causes (Eskurza et al., 2002). • Age-related endurance decline varies by activity, being lower for cycling than swimming or running (Lepers et al., 2010).

Motor skill	Decline rates	Known underlying causes and mechanisms	Influences and dependencies
Balance	• Balance declines with age. • Annual rates or quantitative data on the decline of postural control in older adulthood are not available. • Motor variability decreases and spatial body sway increases with age when assessing balance and thus postural control through control of the body's center of gravity (Delmas et al., 2021).	• Decline in balance is due to peripheral stimulus processing (vestibular, visual and somatosensory systems), central coordination (central nervous system) and neuromuscular response (musculoskeletal system), all affected by the aging (Horak, 2006). • Visual system changes include decreased contrast vision, distance estimation, and spatial relationship recognition (Lord, 2006). • Neuromuscular response involves muscle strength control and reaction times, impacted by age-related changes in muscle mass and function. • Musculoskeletal system changes including reduced proprioception, strength, and sensitivity in the lower extremities (Lord et al., 1996). • Proprioception Decline due to degenerative nerve cell processes and neurochemical changes (Kandel et al., 2014; Ribeiro & Oliveira, 2007).	• Older adults show larger and faster body sway, increased sway frequency and irregularity of sway pattern, and increased tremor, suggesting impaired compensatory adaptations (Degani et al., 2017). • No significant gender differences reported. • Age-related changes are more pronounced in peripheral stimulus processing and the vestibular system, making the visual system more crucial for postural control with age (Nikolaus, 2005).

Motor skill	Decline rates	Known underlying causes and mechanisms	Influences and dependencies
Flexibility	• Flexibility decreases with age. • Trends (due to the small number of scientific studies) show a decline in mobility between age 20 to 70 around 3-5 % per decade, as measured by the chair-sit-and-reach test (Schmidt, 2016; Tittlbach, 2002). • Flexibility is also thought to declines more slowly than other motor skills (Schmidt, 2016), although the method of recording has a large influence on the rate of decline (Tittlbach, 2002).	• Multifactorial reasons for the decline in flexibility on the base of changes in all the tissues involved, particularly bone, muscle and connective tissue (American College of Sports Medicine, 2003). • Age-related changes lead to an increase in muscle-tendon stiffness and a decrease in joint flexibility, which can lead to reduced overall flexibility (Cornu et al., 2003). • Both elastin and collagen fibers undergo age-related degeneration, described as fiber fragmentation through fraying, calcification, and increased cross-linking with other fibers (Holland et al., 2002). • Connective tissue collagen undergoes significant dehydration with age, affecting its elastic properties (Mohan & Radha, 1980). • Changes in bone mineral density associated with articular cartilage degeneration and arthritic joint changes lead to reduced flexibility (Moskowitz, 2009).	• Restrictions in flexibility can be caused by age and secondary causes such as diseases like rheumatism, osteoporosis or Parkinson's disease. • No gender differences in the decline of flexibility, however in the level of flexibility (Woll, 2006). • Women are generally more flexible, potentially due to higher water content in muscles (Stathokostas et al., 2013) and differences in hormone concentrations, especially oestrogen (Herzberg et al., 2017). • Shoulder flexibility declines slightly faster in women than in men (Stathokostas et al., 2013).

The decline in physical performance is reflected in all health-related motor skills. This decline contributes to or causes the changes and challenges of aging in all activities, including ADL. Aging processes, and therefore the causes of decline, are found in almost all structures and lead to changes in all areas, including cognition, which is discussed in more detail in the following chapter.

2.1.2.2 Age-related cognitive decline

Aging causes changes in the brain, and even non-pathological changes lead to a decline in cognitive performance. In general, it can be said that cognitive decline is not uniform and is always in a dynamic exchange with lifelong learning (Salthouse, 2012). Even in old age, people can show consistently high or even increasing cognitive performance, which is not easy to measure and always depends on the individual's background experience (Staudinger & Pasupathi, 2000).

Physiological aging of the brain is due to structural, biochemical and molecular processes and the associated tissue atrophy, neurotransmitter changes and accumulation of damage in the cellular environment (J. Lee & Kim, 2022). The sum of these changes results in brain volume and weight loss, which is about 5 % per decade from the age of 40, increases acutely after the age of 70 (Peters, 2006), and leads to terminal cognitive decline, often a few years before death (Cohen-Mansfield et al., 2018; Dodge et al., 2011). Volume loss varies by brain region. In a cross-sectional study of 2,200 healthy elderly people aged 34 to 97 years, the greatest volume loss was found in the frontal lobe at 12 %, followed by the temporal lobe at 9 %, while age-related volume loss in the occipital and parietal lobes was insignificant (DeCarli et al., 2005). In a longitudinal study of 142 healthy older people aged 60 to 91 years, annual volume loss in the prefrontal cortex and temporal lobe was 0.5 %, while annual volume loss in other areas exceeded 1.0 % (Fjell et al., 2009).

The objectification of cognitive function is achieved through cognitive tests. A distinction can be made between tests that assess reasoning, memory and speed, which are designed to assess the efficiency or effectiveness of processing at the time of assessment (Salthouse, 2012). This first category of tests measures fluidity (Salthouse, 2012). The second category of tests assesses the cumulative products of past processing. This typically takes the form of an assessment of acquired knowledge through general information or vocabulary representing crystallized skills (Salthouse, 2012).

Cognitive decline is generally higher in fluid intelligence with skills such as memory, executive function, and processing speed (Horn & Cattell, 1967) and is particularly pronounced in psychomotor speed and working memory (Novotný et al., 2022). Crystallized intelligence, with skills such as verbal ability, general knowledge and numeracy, may be better maintained with age (Deary et al., 2009), as shown in Figure 2.2. The zero line represents the average performance, while the upper and lower lines represent better and worse performance, respectively. Salthouse (Salthouse, 2012) calculated a decline of -0.02 for liquid ability and 0.02 for crystallized ability in 3000 adults between the ages of 20 and 70 years.

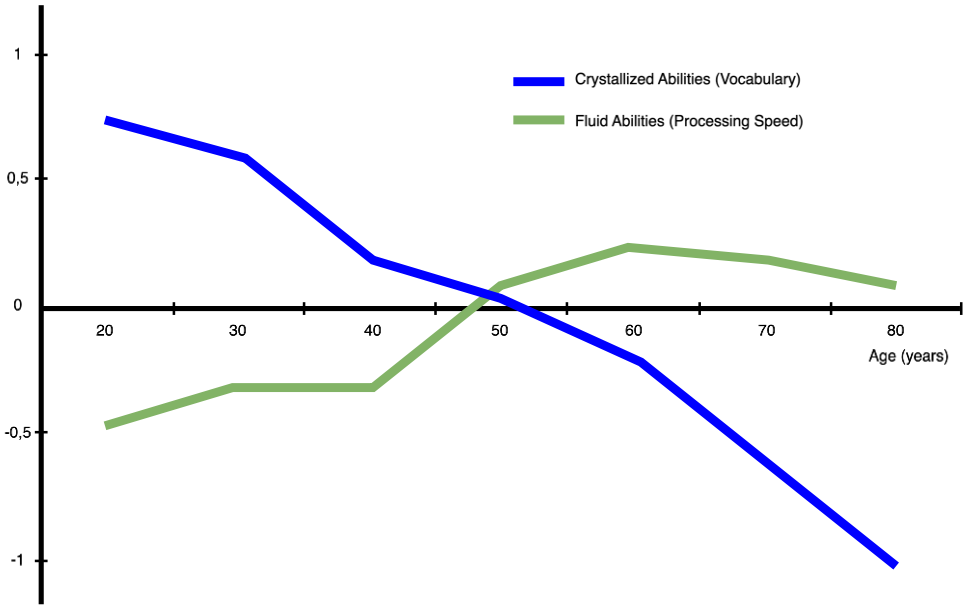

Figure 2.2: Change in cognitive abilities with age in healthy people. Graphic based on Murman with data from Salthouse (Murman, 2015; Salthouse, 2010)

The influences on cognitive performance and its age-related decline are manifold and depend, among other things, on the task; for clearly structured tasks without distracting stimuli, both control demands and age-related losses are low (Lindenberger, 2008). When multiple tasks are performed simultaneously, or when action goals conflict with perception, control demands are high and so are age-related losses (Lindenberger, 2008). Further influences on cognitive decline were investigated in a large longitudinal study of 10,626 participants in the English Longitudinal Study of Ageing over 8 years (Zaninotto et al., 2018). While there is no overall difference in cognitive function and decline between the sexes (Finkel et al., 2003), differences have been found in specific cognitive domains (McCarrey et al., 2016; Zaninotto et al., 2018). Influences on cognitive function have also been demonstrated by age, education, wealth, childhood socioeconomic status, cardiovascular disease, diabetes, physical function, body mass index, PA, alcohol, smoking, depression, and dementia (Zaninotto et al., 2018). Across the different cognitive domains, low physical function, physical inactivity and smoking were associated with faster cognitive decline in both sexes, as were depression and alcohol consumption in men (Zaninotto et al., 2018). For all cognitive functions, faster cognitive decline was observed with increasing age and dementia (Zaninotto et al., 2018). This is described in more detail in the following chapter in the context of disease-related and symptomatic physical and cognitive decline.

2.1.3 Dementia and disease-related physical and cognitive decline

Brain aging is associated with anatomical and functional decline that can lead to neurodegenerative disease, and conversely, like aging, neurodegenerative disease and dementia are associated with more rapid decline in all cognitive domains (J. Lee & Kim, 2022; Zaninotto et al., 2018). Age is the strongest risk factor for dementia (WHO, 2017). This is also true for many other diseases; the likelihood of developing a disease increases with age (see Figure 2.3), as also reflected in the prevalence of diseases such as arthritis, osteoporosis, cardiovascular disease and Parkinson's disease. Each condition brings challenges and limitations that reduce independence and increase the likelihood of needing care, leading to a decline in health-related and overall quality of life (Butterly et al., 2023; Dewilde et al., 2019; Murphy et al., 2009; Mutubuki et al., 2020). The need for care in dementia is the rule rather than the exception, and dementia is therefore receiving increasing attention as societies age. The World Health Organization's global action plan projects a dramatic increase in prevalence from 55 million PwD worldwide in 2019 to 135 million in 2050 (Long et al., 2023). The burden on healthcare systems is significant, as evidenced by the global annual cost of dementia, which was US$ 1313.4 billion in 2019, or US$23,796 per person (Wimo et al., 2023).

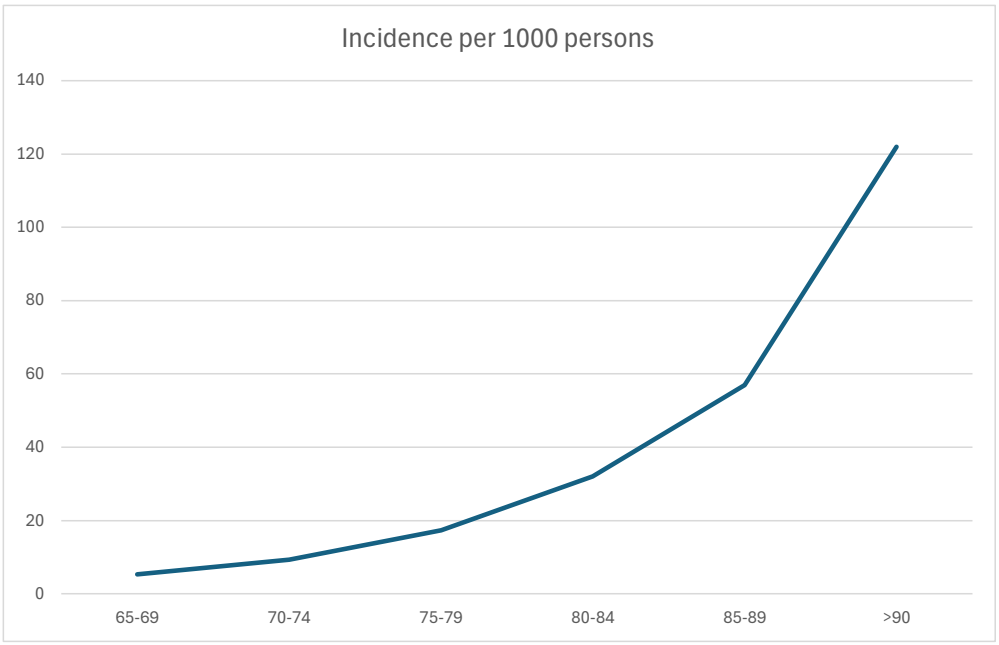

Figure 2.3: Age-specific incidence of dementia in Western Europe. Graphic based on World Alzheimer Report (Prince, 2015)

Dementia is defined as "(...) an umbrella term for multiple, usually progressive, conditions that impair memory, other cognitive abilities and behavior and significantly affect a person's ability to maintain activities of daily living." (WHO, 2017, p.7). The most common forms of dementia are Alzheimer's disease (AD), Vascular dementia, Lewy Body Dementia and Frontotemporal dementia (Chouliaras & O'Brien, 2023). These are followed by several other less common forms such as Progressive supranuclear palsy, Corticobasal degeneration, Huntington's disease, hippocampal sclerosis, prion disease and others (Mak et al., 2017). Dementia is not a pure consequence of aging, as shown by a meta-analysis that reported a prevalence of 119 per 100,000 people between the ages of 30 and 64 (Hendriks et al., 2021). Dementia and cognitive impairment are generally associated with lifestyle risk factors that can be modified: low educational attainment, high blood pressure, hearing loss, smoking, obesity, depression, physical inactivity, diabetes and low social contact (Livingston et al., 2017). The risk of developing dementia is increased by non-modifiable genetic factors (WHO, 2017).

In all degenerative dementias, symptoms associated with brain pathology develop in the first few years after the onset of pathological changes in the brain (Sirkis et al., 2022). In addition, an accelerated cognitive decline is observed even before diagnosis according to a literature review that focused on change points in cognitive and neurological outcomes and included 16 longitudinal cohorts (Karr et al., 2018). The research team found that these change points could be observed 3-7 years before diagnosis of MCI, 1-11 years before diagnosis of dementia, and 3-15 years before death (Karr et al., 2018). For the onset of AD, a sequence of decline was found that affected verbal memory, visuospatial skills, executive function and fluency, and verbal IQ (Karr et al., 2018).

The cognitive symptoms of the neurodegenerative disorders of dementia generally include a decline in cognitive functions with additional impairments in multiple cognitive domains, such as executive function, attention, language, social perception and judgement, psychomotor speed, visual perception or visuospatial skills (WHO, 2019). These cognitive symptoms are often accompanied by behavioral and psychological symptoms of dementia or neuropsychiatric symptoms, which can occur at any stage of AD, although in frontotemporal dementia or dementia with Lewy bodies they appear rather early and are essential for diagnosis (Zhao et al., 2016).

Physical functioning is also affected by dementia, and the rate of physical decline is influenced by the disease (Beauchet et al., 2008). Several physical functions are impaired in dementia, particularly gait, balance and ADL (N. G. Lee et al., 2020). The explanation lies in the strong link between gait characteristics and executive functions, including basic and high-level cognitive processes such as attention, working memory, decision making and problem solving (N. G. Lee et al., 2020). Gait dysfunction is manifested by reduced gait speed,

increased variability, and impaired ability to multitask while walking as cognition declines (J. A. Cohen & Verghese, 2019). Balance is also affected by cognitive impairment, as a person is less able to solve problems, make decisions and perform tasks simultaneously, and loss of balance is significantly more common in people with early dementia than in healthy adults (Bruce-Keller et al., 2012). The functional impairments exacerbated by dementia are associated with a decline in performance in ADL, ultimately leading to a decline in basic and instrumental ADL (Feldman et al., 2006).

Dementia is a global disease causing disability and death (Chouliaras & O'Brien, 2023). With the current prevalence of older people and the associated increase in age- and disease-related limitations in cognitive and physical functioning, our societies face major social, economic and societal challenges. There have been remarkable advances in the diagnosis and treatment of dementia, but there is still no cure (Long et al., 2023). There are also no disease-modifying treatments for the most common types of dementia, such as AD, vascular dementia, Lewy body dementia and frontotemporal dementia (Chouliaras & O'Brien, 2023). Treatment focuses primarily on alleviating symptoms, but medications are often associated with negative side effects (Sink et al., 2005). Therefore, treatment with non-pharmacological interventions is very important (Bessey & Walaszek, 2019).

2.1.4 Summary of age- and disease-related physical and cognitive decline

In summary, the number of older people will continue to increase in both absolute and relative terms. Individual and societal challenges increase with the aging of society and the associated increase in disease. Aging leads to changes throughout the organism that affect cognitive and physical performance. Dementia, as an umbrella term for a variety of different neurodegenerative diseases, is not easy to distinguish from physiological aging processes in the early stages. The functional limitations vary depending on the form, but focus on cognitive decline and physical decline with neuropsychiatric symptoms. Dementia is characterized by a progressive course, leading sooner or later to the need for long-term care. Due to the lack of a cure and the side effects of medication therapies, non-drug therapies, including PA, are important.

2.2 Physical activity and effects on age- and disease-related physical and cognitive decline

Aging is an individual process influenced by many factors, including the number, type and severity of diseases, as well as biographical experiences and events. This results in increasing inter-individual heterogeneity in functionality and hence physical and cognitive performance (Edwards, 2002). Functionality significantly influences the maintenance of an active and independent lifestyle in old age, which in turn is fundamentally dependent on a person's functional fitness, for which balance and cognition are important (Gouveia et al., 2013; Ihle et al., 2021). For healthy aging, maintaining or increasing PA is necessary to preserve functional and cognitive abilities and social activities (Gouveia et al., 2013, 2020). Thus, PA may be a key behavior that influences healthy aging, but also aging with disease (WHO, 2015).

This chapter summarizes the effects of PA and exercise on age- and disease-related cognitive and physical decline. Chapter 2.2.1 starts with a categorization of PA and exercise and their relationship to aging. Chapter 2.2.2 describes the known effects on age-related physical and cognitive decline and their association with and importance for health-related parameters. The effects of PA and exercise on age- and disease-related physical and cognitive decline in PwD are summarized in Chapter 2.2.3. Chapter 2.2.4 presents the challenges and specificities of PA assessment and instruction of PA for the sample of PwD. The chapter ends with a summary in Chapter 2.2.5.

2.2.1 Physical activity – facts and classification

PA is defined as “Any bodily movement produced by skeletal muscles that requires energy expenditure” (Bull et al., 2020, p. 1452). Exercise is a physical activity that ist planned, structured, repetitive, and purposive in the sense that improvement or maintenance of one or more components of physical fitness is an objective.” (Caspersen et al., 1985, p. 128). Exercise and physical training are frequently used interchangeably and generally refer to PA undertaken during leisure time with the primary purpose of improving or maintaining physical fitness, physical performance, or health (Bull et al., 2020). PA and exercise, as well as movement, are essential features of sports, particularly in a historical sense, even if sport is predominantly characterized by a form and attitude of competition (Willimczik, 2018). Sports science is seen as an umbrella, even though many research questions are not focused on performance and competition and go far beyond sports movements (Willimczik, 2018).

The benefits of PA have been demonstrated by numerous studies and have become part of public awareness. Regular PA can have a positive impact on everyone’s physical and mental

health and well-being (OECD, 2023). For example, PA contributes helps to improve blood pressure regulation, manage anxiety and depression, and prevent weight gain. It thus contributes to the prevention and treatment of diseases such as cardiovascular disease, depression, type 2 diabetes, and several types of cancer (Bull et al., 2020). If everyone achieved the WHO-recommended minimum of 150 minutes of moderate-to-vigorous PA per week, more than 10,000 premature deaths in the 30-70 age group could be avoided (OECD, 2023). PA is therefore strongly associated with health and healthcare, and the benefits of targeted therapy from primary to tertiary prevention are well established for many conditions (Bielecki & Tadi, 2024).

PA is relevant in the context of aging and is part of the concept of healthy aging in WHO's work on aging (WHO, 2015). The concept of healthy aging extends the WHO's policy framewok on active aging, developed in 2002. Healthy aging, like active aging, encompasses a person's ability to realize their physical potential and maintain their physical performance, psychological well-being, and participation in social life according to their needs, wishes and abilities, with appropriate support for those who need protection, safety and care (Edwards, 2002). In this holistic approach, 'active' goes beyond PA to include continued participation in social, economic, cultural, spiritual and civic life (Edwards, 2002). However, PA can be a key behavior that influences healthy aging, as outlined in the World Report on Ageing and Health (WHO, 2015). Aging is an individual process with high heterogeneity in functionality such as respiratory capacity, muscular strength and cardiovascular performance that increases with age (Edwards, 2002). Factors are manifold and include genetics, including the number, type and severity of diseases, and biographical experiences and events. According to the WHO, even in the 20 countries with the highest life expectancy, adults typically lose their physical independence in their late 70s (WHO, 2023). Kalache and Kickbusch (Kalache & Kickbusch, 1997) coined the term 'fitness gap' to describe the differences between individuals with faster and slower declines in functional capacity (see Figure 2.4).

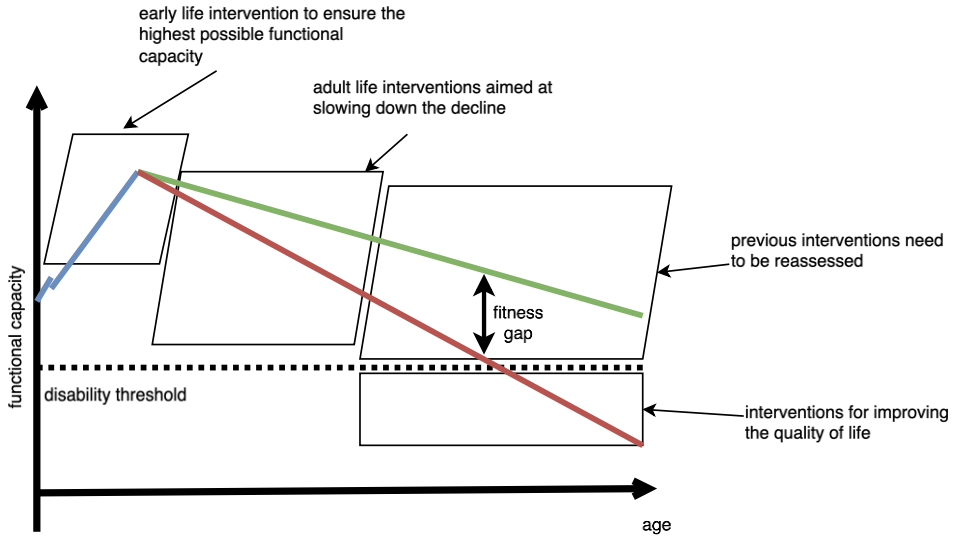

Figure 2.4: Functional capacity during the life circle. Graphic is based on WHO - Ageing and Health Program (Kalache & Kickbusch, 1997)

This fitness gap, which refers to the range of functional capacities, can be interpreted as either as a normal response to the challenges of everyday life or as a pathological process. In many cases, it is not possible to distinguish between these two scenarios (Hanson et al., 2016). The way an individual ages, i.e., how fast and in what way, can be influenced by extrinsic factors at different times (Kuh, 2007). These assumptions and observations are based on developmental plasticity, which states that a genotype is capable of producing a range of different physiological or morphological phenotypes in response to different prevailing environmental conditions during development (Bateson & Gluckman, 2012; Gluckman et al., 2009). Therefore, the concept of plasticity is relevant to explain the influences on the aging process. Plasticity can be broadly defined as the effect of a challenge that often permanently alters the structure or function of a system (Hanson et al., 2016). This means that individuals can change their developmental trajectory throughout life. In the same context, the aging organism it is thought to have a high degree of adaptability, i.e., limitations in certain functional domains can can be compensated by other domains, thus maintaining visible performance (Eichberg & Mechling, 2009). Adaptability is therefore an important factor in the plasticity (changeability) of physical decline in older adulthood (Baltes, 1990). In the following chapter, the effects of PA on physical function in older age and related health outcomes are considered.

2.2.2 Effects on age-related physical and cognitive decline and factors for health

Age-related decline may be mitigated, or at least delayed, because the ability to adapt to physical stimulation is maintained into late adulthood, according to a study that found that each additional hour of PA per week was associated with a 5 % reduction in the rate of physical decline (Buchman et al., 2007). Age-related physical decline, particularly in older adulthood, is associated with several health-related parameters, including morbidity and mortality, functional ability and independence, and quality of life as found in the systematic review of reviews and meta-analyses of longitudinal observational studies that examined the association between PA and any physical or mental health outcome in adults aged 60 years and older (Cunningham et al., 2020). From the 24 included reviews and meta-analyses, it was concluded that physically active older adults (≥60 years) experience healthier aging trajectories, better quality of life and improved cognitive function (Cunningham et al., 2020). There is considerable scientific evidence on the effects of PA and exercise on age-related physical decline in the motor skills endurance, muscle strength, balance and mobility, and on health-related parameters. These effects are summarized below, without distinguishing between the constructs and modalities of PA and exercise.

2.2.2.1 Effects of physical activity on age-related physical decline

The impact on cardiorespiratory fitness and the ability to modify the age-related decline in endurance performance is perhaps best illustrated by the many endurance sporting achievements of older people, such as the 100-year-old British man Fauja Singh, who ran a marathon in Toronto in 2011 or the 92-year-old Harriette Thompson who has an impressive running but also life and disease biography (HDsports, 2022). There is also plenty of scientific evidence that endurance performance can be improved through training, even in older age, and can make a significant contribution to cardiorespiratory health. A review and meta-analysis of 19 included studies found that healthy older people (> 65 years) can significantly improve their physical performance, especially aerobic capacity and walking speed, as well as upper and lower limb strength by training with at least three components (Labata-Lezaun et al., 2023). A review showed that combined exercise significantly improved peak VO2 and some cardiometabolic risk factors in older populations compared with no exercise (Z.-J. Wu et al., 2024). The links between cardiometabolic risk factors and health are well documented and, controversially, low cardiometabolic fitness and endurance are predictors of cancer mortality (Ekblom-Bak et al., 2023; Schmid & Leitzmann, 2015), depression (Pearce et al., 2022; Singh et al., 2023), dementia mortality (R. Liu et al., 2012), and the metabolic syndrome (LaMonte et al., 2005; E. T. Lee et al., 2012).

A systematic review found that muscle strength, balance, and endurance can be improved by PA in people aged 40-65 years (Ferreira et al., 2012). The meta-analysis of 17 included studies found a moderate effect of PA on strength, with larger effects when the intervention specifically targeted strength and also a moderate effect on balance and endurance (Ferreira et al., 2012). Another systematic review examined the effects of functional training on muscle strength, physical function and ADL in older adults (C. Liu et al., 2014). The 13 included studies with different functional exercise content showed positive effects on muscle strength, balance, mobility, and ADL and concluded that functional training can be used to improve functional performance in older adults (C. Liu et al., 2014).

With regard to muscle strength decline, a systematic review compared the effects of single versus multiple sets per exercise on muscle strength, muscle size, muscle quality and functional ability in middle-aged and older adults (D. L. Marques et al., 2023). The 15 included studies reported effects in muscle strength, whereas the effects of multiple sets per exercise were greater for lower limb strength and muscle quality and no differences were found between single and multiple sets for muscle strength and hypotrophy (D. L. Marques et al., 2023). The effects of resistance training on muscle strength and hypertrophy are well documented and were confirmed in a systematic review in very old people (75 years and older) (Grgic et al., 2020). The studies found a significant effect on muscle strength and total muscle hypertrophy. In addition, a systematic review and meta-analysis of 21 included studies found that resistance training can be effective in improving most domains of quality of life, upper and lower limb muscle strength, handgrip strength, and depression in older people (Khodadad Kashi et al., 2023). Shen et al. (Shen et al., 2023) examined the effects of exercise interventions on mortality, quality of life, muscle strength, and measures of physical function in older adults with sarcopenia in a systematic review and network meta-analysis. Strength training with or without diet and the combination of strength training with aerobic and balance training were the most effective interventions for improving quality of life with high or moderate evidence (Shen et al., 2023). Strength and balance training plus diet were the most effective interventions with moderate evidence for improving handgrip strength, and strength and balance training with or without diet for improving physical function (Shen et al., 2023). Another review examined differences in intervention characteristics on muscle strength, balance, and ADL in older (>75 years) and physically frail individuals (reduced muscle strength, endurance, etc.) (Lau et al., 2023). The 76 included studies suggest that single- or multi-component exercise interventions had positive effects on muscle strength or balance in both groups of older adults (Lau et al., 2023).

These studies demonstrate the adaptability of muscle strength in older age and its association with health-related parameters. For example, several studies have found an association with mortality (Buchman et al., 2007; Volaklis et al., 2015), with hand strength in particular

predicting premature mortality in older adults (Bohannon, 2008; Ling et al., 2010). In addition, higher hand strength is associated with greater life satisfaction and quality of life in older people (L. P. Marques et al., 2019); and reduced leg and arm strength is associated with an increased risk of falls and repeated falls (Moreland et al., 2004). Strength is also associated with reduced functional capacity and ability to perform ADL and thus independence (Hairi et al., 2010; Janssen et al., 2002).

The links and interactions between motor skills are obvious and become even clearer when it comes to balance and the effects of PA and exercise on balance. As the regulation of balance depends on many factors (see Chapter 2.1.2), the variability of age-related decline in balance is also multifactorial. Interventions with the main component of PA show effects measured at the level of balance, but also at the level of gait, general mobility and fall risk, as these factors are directly influenced by balance. A systematic review and meta-analysis examined the role of PA on balance and fall rates in patients aged 65 years and older (Papalia et al., 2020). The 16 articles included showed improvements in dynamic balance, static balance, fear of falling, balance confidence, quality of life, and likelihood of falling. Another review included RCTs that conducted lower extremity strengthening, balance, or multicomponent exercise interventions in people aged ≥65 years (Sadaqa et al., 2023). They showed that exercise was effective in improving components of balance, lower extremity strength and mobility, and in reducing falls and fall-related injuries. One review examined postural control after exercise interventions in older adults and concluded from the 22 included studies that balance exercises improved postural control, while strength or multicomponent intervention had no effect (Low et al., 2017). Also, eHealth exercise interventions improve static balance, with moderately significant effects, as well as dynamic balance, and reduced the risk of falls, with small statistical effects, in people aged ≥ 65 years, according to a review of 14 included studies (Ambrose et al., 2013). In addition, gait is also adaptable, as shown by a review focusing on the effects of strength, coordination and multimodal exercise training on habitual and rapid gait speed in healthy older adults (Hortobágyi et al., 2015). The 42 included studies concluded that habitual and rapid walking speed can be increased. High-intensity progressive strength training seems to be the most effective, according to another review and meta-analysis of 25 trials (Van Abbema et al., 2015).

Studies of the effects of PA and exercise on flexibility in older people are scarce and also controversial. One review examined the effects of combined aerobic exercise versus individual aerobic exercise on flexibility and other physical performance outcomes in older people (Bai et al., 2022). Of the 18 studies included, combined aerobic resistance/strength training, multi-component training, and combined dance training had beneficial effects on upper and lower body strength, dynamic balance, fall risk, mobility, gait, agility, and flexibility (Bai et al., 2022). In addition, combined aerobic exercise was more effective than others for stretching,

elbow flexion, knee flexion, shoulder flexion and extension, and functional reach test (Bai et al., 2022). Flexibility has been shown to have little predictive or concurrent validity for health and performance outcomes (e.g., mortality, falls) in healthy people, especially when considered in the context of other important components of fitness (e.g., body composition, cardiovascular endurance, muscular strength) (Nuzzo, 2020).

PA is an important factor that can positively influence the aging process and the development and progression of disease, and thus maintain independent and safe ADL performance (Cleven et al., 2020; Tak et al., 2013; WHO, 2020). A systematic review of meta-analyses investigated which types and characteristics of PA are most effective for older adults (Di Lorito et al., 2022). The 56 included meta-analyses looked at PA interventions for older adults aged 65 years and older. The largest effect sizes for improvement were found for resistance training, meditative exercise interventions and active video games (Di Lorito et al., 2022). Although the benefits of PA and exercise on the physical performance and health-related outcomes are evident and well-documented for most domains, the dose-response relationship for each outcome is still unclear (Z.-J. Wu et al., 2024).

2.2.2.2 Effects of physical activity on age-related cognitive decline

There are many factors that contribute to age-related cognitive decline, including non-drug therapies such as cognitive training and art therapy, which have been examined in a number of studies. The results of the studies are very heterogeneous. However, cognitive and physical interventions seem to be the most promising. A systematic review examined the effects of cognitive and physical interventions on nursing home residents (Wöhl et al., 2020). The 29 included studies with 1,816 participants showed that both physical and cognitive activities were both statistically significant in strengthening cognitive resources to the same extent. In the following, only the area of PA and exercise and related interventions will be considered.

The causal relationship between PA and exercise and overall improvements in cognitive function over the course of alifetime is not fully understood and must be considered with caution (Ciria et al., 2023). An umbrella review of meta-analyses found that the evidence had low statistical power and the benefits of PA were small due to selective inclusion of studies, publication bias, and wide variations in the combination of preprocessing and analysis decisions (Ciria et al., 2023). However, research with samples of older adults points in a different direction, as shown by a study of 2,060 cognitively unimpaired men and women aged ≥70 years life (Krell-Roesch et al., 2021). Smaller declines in memory function were found with light-intensive PA in middle age, and smaller declines in language, attention, and global cognition with vigorous PA in late life (Krell-Roesch et al., 2021). A study of 3535 participants aged 18 to 79 years showed that higher levels of PA were associated with better executive function

and memory in both cross-sectional and longitudinal analyses (Gaertner et al., 2018). A systematic review examined the association between PA in adulthood and the maintenance of domain-specific cognitive function in late adulthood (Engeroff et al., 2018). Nine cross-sectional and 14 longitudinal studies confirmed this association, with moderate- and vigorous-intensity PA being positively associated with the maintenance of cognitive function in old age.

This is also supported by the inverse association between physical inactivity and other health-related behaviors, such as smoking, and greater cognitive decline (Anstey et al., 2007; Beydoun et al., 2014). The neuroprotective function of PA is also considered in relation to the risk of mild cognitive impairments or dementia, which is significantly reduced by PA (Krell-Roesch et al., 2016, 2018). The risk reduction is between 34 and 40 % compared to inactive individuals (Beckett et al., 2015).

In the area of attention, significant improvements can be seen in older people with multicomponent training (de Asteasu et al., 2017). Current evidence on the effects of PA on memory performance is mixed. A positive effect of endurance training on memory performance has been found, especially in healthy older people (Hoffmann et al., 2021). A systematic review and meta-analysis found positive effects of PA on executive function in healthy older adults (F. T. Chen et al., 2020). However, based on 33 included studies, they concluded that the effects in older adults were rather small and influenced by several moderatos. Another review concluded from 12 included studies that resistance training had positive effects on the executive cognitive ability and global cognitive function among older people with a weak impact in memory (Z. Li et al., 2018). An improvement in language (e.g., verbal fluency) has been found with endurance training in older people (Nocera et al., 2015). One review examined the effects of PA in combination with cognitive training, nutrition, and social interaction (Koščak Tivadar, 2017). Regarding the question which type and intensity is most effective, the included studies showed that low-intensity aerobic exercise has a positive effect on visuospatial perception and attention, while moderate PA has a positive effect on general cognitive capacity, working memory, verbal memory, and attention (Koščak Tivadar, 2017). Despite a large number of studies investigating the effects of PA on various cognitive functions in healthy older people as well as in people with MCI or dementia, the results are heterogeneous and therefore difficult to compare. Among other things, it remains unclear what exact content and amount of PA may maximize the desired effects, as the training interventions used and the PA parameters recorded vary widely between studies.

Although the potentially beneficial effects of PA on cognitive performance in older people are well known, the mechanisms underlying this association are not yet fully understood. The observed effects can be explained by considering the mechanisms of action of PA on the brain in general, the most widely studied of which is the neurotrophic hypothesis (Schinder & Poo,

2000). The neurotrophic hypothesis proposes that neurotrophins, in particular Brain-Derived Neurotrophic Factor (BDNF), are important regulators of neuronal survival, development, function, and plasticity (Schinder & Poo, 2000). It is therefore possible to understand the mechanisms of neuronal plasticity and regeneration in the adult brain. This hypothesis is also used to explain the effects of PA on the brain. A systematic review of 29 included studies showed that endurance training in particular increases the concentration of BDNF, which stimulates neuroplasticity at the molecular and cellular level (Dinoff et al., 2016). In another review of 15 studies, these effects were also found with interval training, with the increase in BDNF concentration described as moderate in young healthy adults (García-Suárez et al., 2021). Another review highlighted the positive association between PA and circulating levels of BDNF, while little evidence was found for other neurotrophins such as nerve growth factor, neurotrophin-3 and neurotrophin-4 (Lippi et al., 2020). The improvement in cerebrovascular function due to exercise, which is associated with angiogenesis, is thought to be the cause of the general building effect in the brain (gliogenesis, neurogenesis and synaptogenesis), which is expressed in an increase in the volume of both white and grey matter (Girolamo et al., 2014; Zatorre et al., 2012).

In summary, functional improvements in the brain due to PA are based on an improvement in cerebrovascular function and thus in the supply of oxygen and nutrients, as well as on a slowing of dopamine degradation and a stimulated release of neurotrophins, especially BDNF (Claassen et al., 2021; Cotman et al., 2007; van Praag, 2009). This is associated with structural changes that are reflected in white and grey matter, particularly in the hippocampus (Moreno-Jiménez et al., 2021). These adaptations also have a positive effect on cognitive performance also in older people, improving learning and memory and preventing neurodegenerative diseases (Ahlskog et al., 2011; Colcombe & Kramer, 2003; Cotman et al., 2007; Smith et al., 2010; van Praag, 2009). These mechanisms of action are also thought to be present in PwD and have the potential to influence disease-related decline processes. However, significant impairments in adult hippocampal neurogenesis have been found in AD patients (Moreno-Jiménez et al., 2021).

With PA as one factor, and taking into account several internal and external factors, many people can maintain their physical and cognitive abilities, and thus their daily functioning and independence, into old age (Gouveia et al., 2013, 2020). The question is what this looks like in the presence of a disease such as dementia and whether the disease-related decline can be influenced. This will be examined in the following chapter on the effects of exercise interventions in dementia.

2.2.3 Effects of physical activity and exercise on people with dementia

Dementia remains incurable, which means that treatment is mainly based on symptom relief, with medication therapy that is often associated with negative side effects (Sink et al., 2005). Therefore, treatment with non-pharmacological interventions is important (Bessey & Walaszek, 2019). In particular, exercise interventions have shown promising effects in improving cognition and physical function or slowing disease-related decline (Deslandes et al., 2009; Farina et al., 2014; Sofi et al., 2011; S. Zhou et al., 2022). The mechanisms of action presented in Chapter 2.2.2 are also used to explain the effects of PA in PwD. These are based on the neurotrophic hypothesis, which explains the stimulation of blood flow and neuroplasticity (angiogenesis, neurogenesis, synaptogenesis), the promotion of the release of growth factors such as BDNF, and the release of neurotransmitters such as irisin. The following summarizes the effects of PA in PwD based on various outcomes, with a focus on recent reviews.

Quality of life is identified by PwD, their families, and NHE as a central goal of treatment. Factors that contribute to quality of life include mood, engagement in pleasurable activities, and the ability to perform ADL (Logsdon et al., 2007). These influencing factors are associated with PA. In addition, quality of life and ability to perform ADL can be positively influenced by exercise interventions (Liang et al., 2022; Logsdon et al., 2007; Teri et al., 2003; S. Zhou et al., 2022).

One review examined the effects of PA on improving functional capacity in older people with AD (Braz de Oliveira et al., 2023). From the 13 included studies with a total of 811 older people with AD, it was concluded that multimodal exercise promotes improvements in functional ability, although the evidence was moderate to low. They concluded that PA can be recommended for older people with AD, and that the involvement of NHE in PA should be considered, as this increases the benefits (Braz de Oliveira et al., 2023). Another review focused on the effectiveness of multicomponent exercise interventions for physical fitness, cognition, and ADL functionality (Borges-Machado et al., 2021). The conclusion based on the 17 included manuscripts was that there were effects on performance in ADL, but not on cognitive function and physical fitness in PwD (Borges-Machado et al., 2021). The effects of exercise interventions on multi domains in people with AD were investigated in a systematic review of 28 included studies (López-Ortiz et al., 2023). Significant benefits were found for ADL, mobility, and global cognition, but only for aerobic exercise. Regarding health outcomes in PwD, another review focused on home-based PA and found effects in 16 included studies on delaying cognitive function decline and improving changes in behavioral and psychological

symptoms of dementia, ADL, health-related physical fitness, and caregiver's burden in PwD living at home (Almeida et al., 2020).

The effects on cognition and ADL were analyzed in people with AD in a review with 16 included articles (S. Zhou et al., 2022). They found that PA interventions were associated with significant improvements in global cognition and ADL, with relatively strong effects on improving global cognition in AD patients with PA sessions 3-4 times a week for 30-45 min for more than 12 weeks. Another review of the effects of PA on cognitive function in people with AD concluded that PA may improve cognitive function or slow cognitive decline in people with AD, based on 13 included studies with a total of 869 participants (Du et al., 2018). Five studies showed no benefit, so they concluded that more RCTs with clear intervention criteria, large samples and long-term follow-up are needed. Another review examining the effects of PA on different cognitive domains in PwD, based on 11 included meta-analyses, found beneficial effects on general cognition, executive function and delayed memory, but no effects on verbal fluency, attention and immediate recall (Venegas-Sanabria et al., 2021). Another umbrella review, which included 27 systematic reviews and a total of 28,205 participants, looked at PA interventions and found positive effects on several cognitive and non-cognitive outcomes with very low to moderate evidence; with resistance training showing the largest effect on global cognition (Demurtas et al., 2020). In addition, PA improved non-cognitive outcomes in PwD, including falls and neuropsychiatric symptoms. In terms of executive function, another review of six included studies concluded that there is a positive effect of PA in people with AD (Guitar et al., 2018). A trend towards improvement in executive function were observed in all six studies, and significant improvement was found in four of the included studies (Guitar et al., 2018).

There are many exercise interventions for PwD. Conclusive evidence on the effects of PA and exercise interventions on physical and cognitive performance in PwD is still lacking, but the available results suggest that physical and cognitive performance improves even in severely affected PwD (Blankevoort et al., 2010; Forbes et al., 2015; Groot et al., 2016; Hall et al., 2021; Henskens et al., 2018). In addition, there is little evidence on mechanisms of action are scarce, and one explanation may be that risk factors for dementia are positively influenced by PA and exercise. Once dementia has been diagnosed, the aim is to identify modifiable factors to slow its progression (Long et al., 2023). Focusing on this approach, PA and exercise are very helpful. In addition, quality of life and the ability to perform ADL may be positively influenced by exercise interventions (Liang et al., 2022; Logsdon et al., 2007; Teri et al., 2003; S. Zhou et al., 2022). The inconclusive evidence may be a result of several challenges associated with the sample of PwD. These challenges relate to the specificity of the target group of PwD, but also to the form of exercise intervention, and are discussed in the following chapter.

2.2.4 Challenges within exercise interventions for people with dementia

The reviews and meta-analyses described above tend to show a positive trend for PA and exercise on cognitive and motor decline in PwD. However, the evidence is inconclusive due to a number of interrelated challenges associated with exercise interventions in PwD, often in the context of care. At an individual level, there is a great deal of variation in cognitive impairment, with very individual characteristics and disease progression, but also frequent multimorbidity and additional limitations (Potter et al., 2011). There are also complex interactions between age-related changes and psychosocial and demographic factors such as gender, education or marital status. In addition, environmental factors, such as the built, social, technological and natural environment, play a crucial role as influential factors in age-related decline, especially with regard to PA (Schlicht & Oswald, 2018). Consequently, heterogeneity can be significant and concepts of personalization and individualization are relevant and become increasingly important with age. Currently, there are no adequate concepts that sufficiently take into account the heterogeneity of PwD and their individual and environmental determinants.

In addition to the great heterogeneity of the target group, there is also great variation in the content of the exercise intervention. Although some studies have looked at individual components of exercise interventions, as described above, no clear picture emerges. In general, exercise interventions with multiple components seem to be more successful, but again questions remain about the specific dosage of exercise. Interventions over a longer period of time, with several sessions per week, also seem to be more effective (S. Zhou et al., 2022). However, concrete information on intensities and other "dosage forms" cannot yet be clearly derived. In general, the degree of individualization of non-pharmacological treatments tends to be low (Cohen-Mansfield et al., 2012; Scales et al., 2018). This is also the case for exercise interventions, which are predominantly delivered and led by NHE (Hirt et al., 2023). In particular, the delivery of exercise interventions by NHE themselves is of current and future interest. This was also due to the COVID-19 pandemic and pandemic-related restrictions. These were responsible for changes in daily routines and consequently to the reduction and cessation of various activities and treatments, preventing many residents from being physically active (Frahsa et al., 2020). In general, the proportion of sedentary time, which accounts for up to 90 % of the day in nursing homes (Souto Barreto et al., 2015), is best be reduced by interventions led by NHE. For this reason, there is great potential to expand knowledge and integrate expertise in exercise interventions. Currently, there is a lack of evidence- and theory-based, scientifically evaluated interventions in this area that can be implemented in nursing home settings. This poses a number of challenges, particularly in relation to the known

and researched barriers to implementing and sustaining of exercise interventions in nursing homes, particularly the lack of staff and staff time resources (Hirt et al., 2023). However, digitalization may offer a potential bridge for knowledge provision and access to evidence- and theory-based exercise interventions.

On the study side, the use of the selected assessment methods must also be considered, particularly in the area of physical performance. The picture that often emerges here is that assessment methods are used that have not been developed for PwD (Trautwein, Barisch-Fritz et al., 2019). Particularly when instructing physical assessment procedures, it becomes clear that the actual physical performance is overshadowed by cognitive limitations. The controversial results of the interventions, especially for physical performance, are to some extent based on inappropriate assessment methods and their inadequate or insufficiently considered reliability or sensitivity.

In terms of expectations of exercise interventions, it is often unclear how success was defined in the individual study. If one considers that slowing the rate of decline or maintaining cognitive or motor performance can be defined as a positive outcome, it becomes clear that slowing down is very difficult to detect. It is doubtful whether the statistical methods currently used, with the cut-offs usually set, are sufficiently sensitive to detect such changes. Related to the success of the intervention is the adherence of PwD to the intervention, which was examined in a review (Di Lorito et al., 2020). This review of 41 included studies found that only half of the studies operationally defined adherence. The review found a lack of consistency in reporting adherence and key variables mediating adherence, including compliance, attrition and adverse events (Di Lorito et al., 2020). The totality of the challenges should be directly considered when planning interventions and also when evaluating the impact of exercise interventions.

2.2.5 Summary of effects of physical activity on age- and disease-related decline and exercise interventions for people with dementia

PA has a positive influence on age- and disease-related changes. However, the development of PA-focused interventions is subject to many determinants, as PA and its implementation depend on a variety of factors and environmental influences. For PwD, the evidence on the effect of PA on age- and disease-related decline is inconclusive. This conclusion, based on numerous reviews and meta-analyses, is tempered by the current challenges with exercise interventions and studies, and with effect assessment. In summary, measuring physical performance in PwD is challenging and there is a lack of literature on interventions that take into

account the heterogeneity of PwD. In addition, there are currently few sustainable interventions that can be implemented in nursing homes under the supervision of NHE.

2.3 Digitalization and digital intervention planning for exercise interventions

The development of exercise interventions is a complex undertaking, starting with the right exercise content, with appropriate intensities and other control variables, to embedding them in a socio-economic environment, taking into account psychosocial and demographic factors that are crucial for training, implementation and maintenance. Digital interventions and their design and development must take into account additional constraints, as additional factors based on the human-technology interface are added and are relevant for the success of the intervention. The development of public health interventions is largely based on social and behavioral theories, and digital exercise interventions should be seen in this context. It is widely accepted that interventions developed on an explicit theoretical basis are more effective than those without, and that strategies that combine multiple theories and concepts are even more effective (Glanz & Bishop, 2010; Gourlan et al., 2016).

This chapter provides an overview of digital intervention planning, starting in Chapter 2.3.1 with a general consideration of digitalization and some facts and possibilities regarding exercise interventions and digital solutions in the nursing home setting and specifically for PwD. The background of theory- and evidence-based intervention planning in the context of behavioral science is presented in Chapter 2.3.2, followed by a brief description of the IMF. The application of IMF in the context of digital intervention planning for exercise interventions is investigated in Chapter 2.3.3. The chapter concludes with a summary of the digital opportunities and challenges for exercise interventions for PwD in Chapter 2.3.4.

2.3.1 Digitalization – facts, definitions and potential for promoting physical activity

Digital technologies have found their way into almost every area of everyday life, which is why we can already speak of a digital age. Digitalization, as the use and interconnection of data and digital technologies leading to new or changed activities, has transformed many everyday activities (George Mois & Rogers, 2024). This includes the healthcare sector, where digital health is already of great importance. Digital health solutions can be broadly divided into two categories eHealth and mHealth (Chan, 2021). According to the WHO, eHealth is defined as the cost-effective and safe use of information and communication technologies to

support health and health-related fields (WHO, 2016). The definition of mHealth is the use of mobile and wireless technologies for medical and public health practice (WHO, 2016). In general, digital solutions in the healthcare sector can be categorized according to their functions into (1) solutions that improve system efficiency, but have no measurable benefit for the patient, (2) solutions that inform or provide basic monitoring and encourage behavior change and self-management, and (3) clinical decision support and predictive models that guide treatment, provide active monitoring, calculations, and/or make diagnoses (Guo et al., 2020). In addition, there are a growing number of digital health solutions such as mobile applications related to fitness, and sports (Higgins, 2016).

A variety of digital interventions that can be delivered via digital devices such as smartphones, tablets, desktop computers or wearables are increasingly being used in healthcare (Murray et al., 2016). A central goal of digital interventions in healthcare is to positively influence health-related behaviors and outcomes (Sieverink et al., 2017). Examples include smoking cessation (Vilardaga et al., 2019), increasing PA (Milne-Ives et al., 2020), or managing chronic conditions (C. Zhou et al., 2022). With regard to the effectiveness of digital interventions, the research situation is often inconsistent or controversial. The reasons for low effectiveness are manifold and range from a limited theoretical basis, a low level of standardization of evaluations, poorly documented adherence and short observation periods to high dropout rates and high variability of intervention components (Enam et al., 2018; Kernebeck et al., 2021). Nevertheless, mHealth is considered a powerful tool for behavior change because its strengths, such as ease of access and user-friendliness, can lead to global dissemination and thus, in principle, unrestricted access to health (Baharuddin et al., 2013; Carroll et al., 2017). In principle, a person can use mHealth anywhere and at anytime, so a well-designed application will be well received by users, can change their preferences, and can reduce barriers to accepting health services (Hauser-Ulrich et al., 2020; Overdijkink et al., 2018).

With the growing number of fitness and sport applications mentioned above, the promotion of PA, for example through exercise interventions, has a great potential to improve healthcare (Statista, 2023a, 2023b). Existing fitness and sport applications are broad in scope, including PA promotion, training, rehabilitation, exergaming, and diagnostics, as are the audiences that use or can use these applications, ranging from the health-conscious to serious athletes, but also people with disease (Higgins, 2016; Machado et al., 2016). Mobile applications offer solutions ranging from simple data tracking to positively influencing their users by promoting behavior change (Duncan et al., 2016) and improving health awareness related to PA and/or diet (Wang et al., 2016), often in conjunction with other factors such as sleep (Ong & Gillespie, 2016), social interaction (Higgins, 2016), to sophisticated medical rehabilitation programs (Zens et al., 2017).

The implementation of digital interventions requires special consideration of the environment in which they will be implemented. Digital solutions to promote PA in nursing homes are rare, even though the nursing home environment has changed significantly in recent years due to digitalization. Digitalization in the care sector is attracting much public interest, with a focus on solutions to the growing problems of an aging society, i.e., the increasing need for care among older people with a simultaneous shortage of care providers (Zöllick et al., 2020). Visions of digitalization and technologization of care have received a positive response from the public and the scientific community in recent years and have led to the initiation and implementation of numerous research activities (Krings & Weinberger, 2022). However, the actual use and adoption of digital and technological solutions and services in elderly care is hampered by access gaps or limited knowledge, as well as a perceived lack of technology adoption (C. Lee, 2022). Adoption of information and communication technologies in healthcare is known to take longer than in other sectors due to security concerns (Bronsoler et al., 2022).

The impact of digital solutions on clinical outcomes, productivity and the healthcare workforce showed rather modest improvements and cost savings, and no impact on productivity (Bronsoler et al., 2022). This suggests that the successful integration of technology in healthcare is subject to many influences and disruptions. In nursing homes, for example, any successful technology solution should address the needs of older people while taking into account the specific circumstances and needs of NHE. However, the barriers in nursing homes are diverse and include, among others, the conditions and resources of a specific nursing home, the attitudes and perspectives of the decision makers, the actual caregivers and the care recipients (Ko et al., 2018). The specific situation and circumstances need to be taken into account, especially when it comes to exercise interventions for people in need of care, or for PwD in particular.

Digital solutions for PwD have been increasingly used in the past, with applications ranging from diagnostics, such as body-worn sensors to detect early signs of functional decline (Jansen et al., 2022), to monitoring, such as electronic health records (Shiells et al., 2020). A recent systematic review examined digital health interventions for people with MCI of dementia (Di Lorito et al., 2022). This review examined the evidence for the effectiveness of digital health interventions on physical, cognitive, behavioral and psychological outcomes and ADL. The digital interventions showed a moderate effect on cognition and a negative moderate effect on basic ADL (Di Lorito et al., 2022). One main finding was that the delivery of supervised interventions was associated with the greatest benefit. They also suggested that accessibility, acceptability and sustainability of digital interventions for end-users must be prerequisites for the development of future successful services (Di Lorito et al., 2022). Therefore,

the determinants of the nursing home environment need to be considered when developing a digital exercise intervention for PwD in nursing homes.

The possible potential of digitalization for the specific context of exercise interventions and aging is illustrated in Figure 2.5. The figure illustrates the imbalance between the increasing decline in PA with age at the content level and the problem of the often lack of provision in practice or the transfer of knowledge into practice, which is often due to several challenges at the methodological level. This is where digitalization offers an opportunity to address the fundamental problem of physical inactivity at multiple levels, particularly in terms of knowledge transfer and provision of PA interventions.

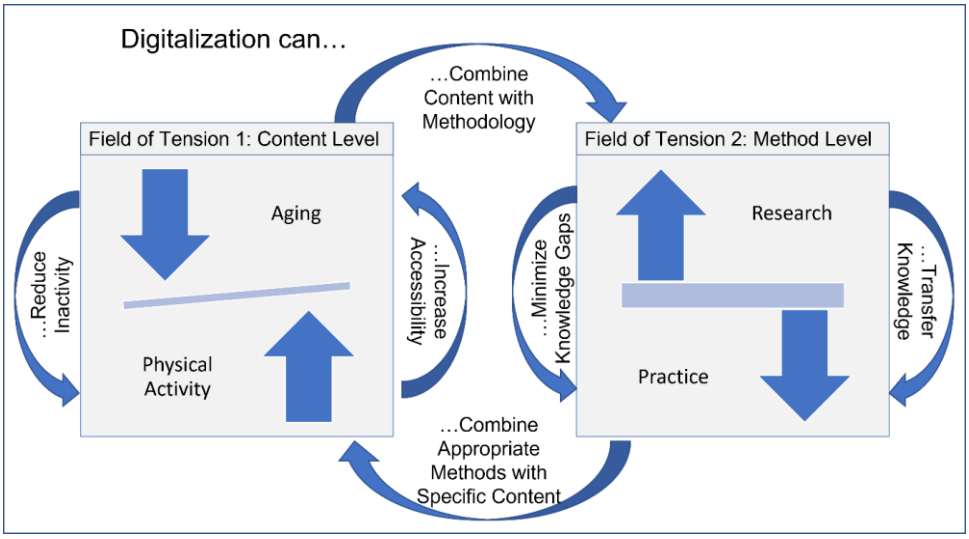

Figure 2.5: Potentials of digitalization in the context of physical activity and aging based on the Interactive System Framework (Noonan et al., 2012)

The design and development of digital applications can be seen as a tool for implementation, as it can help to bridge the gap between research and practice, which is described in the Interactive Systems Framework (Noonan et al., 2012). Thus, it can be seen as a solution on the method level. Furthermore, in the context of PA and exercise, digital solutions can also help to provide access to PA for people who may have more difficult conditions to practice PA. At the level of content, digitalization can therefore be seen as a solution to reduce the imbalance between aging and the provision or availability of PA.

2.3.2 Theory- and evidence-based intervention planning with regard to exercise interventions

Evidence on the effectiveness of mHealth interventions has led to heterogenous and controversial conclusions. The main criticism of mHealth interventions is that the technology often lacks a theoretical base in human-technology interface design, health behavior, and communication theory (Vollmer Dahlke et al., 2015). The importance of a theoretical base is explained by the need to understand health behavior and the context in which it occurs before attempting to change behavior. Therefore, interventions designed to change a particular health behavior may be more effective if there is a sound understanding of the relevant theories of behavior change and the ability to integrate them appropriately. Theories of interventions in public health are primarily based on behavioral and social science theories. These theories and models are briefly summarized below, with a focus on PA and exercise interventions. In addition, the design and development of interventions that integrate theory and evidence are considered and described in the following.

2.3.2.1 Theories and models relevant in the context of physical activity and exercise interventions

There is a growing body of evidence to support the hypothesis that interventions are more effective when they are theoretically founded, and that interventions have an even greater impact when multiple theories and concepts are combined (Glanz & Bishop, 2010; Gourlan et al., 2016). Behavioral change theories originated in social psychology and have been applied in the context of PA in a variety of settings, with a focus on promoting self-management and maintaining health-promoting behaviors. The four most commonly used theories are the Social Cognitive Theory (Bandura, 2000), the Transtheoretical Model (Prochaska & Velicer, 1997), the Theory of Planned Behavior (Ajzen, 1991), and the Self-determination Theory (Ryan & Deci, 2000). These theories describe a variety of interrelated processes and factors that play a role in behavior change and enable the planning of better interventions, particularly by identifying relevant influencing factors (Buchan et al., 2012).

The Social Cognitive Theory assumes that behavior is influenced by expectations, goals and incentives (Bandura, 2000). The theory specifies the mechanisms through which these factors operate and how they can be translated into effective health behavior (Buchan et al., 2012). This theory is one of the most important for studying motivation and behavioral outcomes with several examples for its structure and predictive power in many settings and populations including older adults (McAuley et al., 2003). A key variable within this model is self-efficacy which is the strongest factor to consider when predicting behavior (McAuley et al., 2003).

The Theory of Planned Behavior is used to identify decision-making processes and to understand the factors that influence the acceptance, motivation and adherence to PA (Ajzen, 1991). The theory states that intention is the most direct determinant of behavior and that attitudes, subjective norms and perceived behavioral control influence intended behavioral and therefore actual behavior. In a number of populations focusing on PA, good results have been obtained in explaining intention (N. L. D. Chatzisarantis et al., 2007), but also in predicting behavior (Hagger et al., 2002; Hausenblas & Carron, 1997). The theory has performed well in explaining the relationship between intended exercise and actual behavior in older adults, but may not capture all aspects that explain PA behavior in older adults (Stehr et al., 2021). The main criticism of the theory relates to the measurement of its constructs, where intention and behavior has been shown to depend on the time of measurement (N. Chatzisarantis et al., 2005), but also on the age, gender and ethnicity of the participants (Hagger et al., 2002).

Self-determination theory emphasizes that the satisfaction of basic psychological needs for competence, autonomy, and social relatedness is important for the development of intrinsic motivation (Deci & Ryan, 2000). Satisfying these three basic psychological needs leads to optimal motivation and positive psychological, developmental, and behavioral outcomes (Deci & Ryan, 2000). Conversely, social environments that inhibit the satisfaction of these needs lead to less optimal forms of motivation and negatively affect a range of well-being outcomes. Self-determination theory helps to understand and promote long-term behavior change by focusing on the processes through which a person acquires the motivation to initiate and maintain new health-related behaviors over time and by considering the environment as an important factor in satisfying needs and promoting motivation. This theory of human motivation has been widely applied to understand exercise behavior (Buchan et al., 2012).

The Transtheoretical Model describes the acquisition and maintenance of health behavior as a cyclical process in which individuals move through a series of specific stages, each characterized by a particular pattern of psychosocial and behavioral change (Prochaska & Velicer, 1997). Individuals are placed in one of five stages according to their readiness for change: precontemplation, contemplation, preparation, action and maintenance (Marcus & Forsyth, 2009). The Transtheoretical Model is the most commonly used stage model in the context of PA (Buchan et al., 2012). Interventions based on this model moved participants closer to the action and maintenance phases of PA compared to control group participants (Kirk et al., 2004). However, studies on the positive effects of this model are controversial (Adams & White, 2003; van Sluijs et al., 2006) and conclude that stage-based interventions are not more effective in promoting long-term maintenance of PA.

There are many other theories and models that focus on PA and exercise and explain PA-related behaviors, which can be categorized into structural, process and stage models (Buchan et al., 2012; Geuter, 2011). Structural models include the Social Cognitive Theory (Bandura, 2000), the Theory of Planned Behavior (Ajzen, 1991), and the Theory of Protection Motivation (Rogers, 1985). These structural models examine the causal relationships between psychological or social conditions that persist over time and are thought to influence regular sport and exercise behavior, and represent the influence process statically. The differences between these structural models lie in the consideration of the influencing factors that are thought to be responsible for the practice of regular sport and exercise behavior. These include self-efficacy, outcome expectations, subjective norms, risk perception and behavioral intention (Geuter, 2011). The intention to exercise can be well explained, but the discrepancy between this intention and actual behavior cannot be explained. Despite numerous studies on the prediction of sport and exercise behavior, the explanatory potential is limited (with explained variance of 28-38 %), which may be due to insufficient consideration of volitional control variables (planning, action control) (Geuter, 2011).

In addition, there are process models that give greater consideration to volitional aspects and influencing variables by describing the psychological processes that lead to the initiation, maintenance, and possibly cessation of PA and exercise behavior. In particular, the Relapse Prevention Model (Marlatt & George, 1984), the HAPA model (Schwarzer, 1992), and the MoVo process model (Fuchs, 2007) are relevant in the context of PA and exercise interventions.

Stage models, such as the Transtheoretical Model (Prochaska & DiClemente, 1983), the Berlin Stadienmodel (Fuchs, 2001), or the Model of the Precaution Adoption Process (Weinstein & Sandman, 1992) assume that the process of behavior change can be divided into different stages that are completed in a specific order. The division of change processes in exercise and sport behavior into different stages is particularly helpful for intervention practitioners, as it provides good action strategies for tailored exercise interventions (Geuter, 2011).

Although these theories and models provide a context for understanding, explaining, and ultimately influencing behavior in the context of PA, there are still gaps in addressing current health issues (Buchan et al., 2012). Many theories that have been shown to be effective in predicting behavior have been applied to PA and exercise interventions. However, numerous limitations have also been identified for each theory and model (Hagger & Chatzisarantis, 2014). These limitations of behavioral theories regarding PA, referred to as the intention-behavior gap, have been identified in many PA intervention studies (Rhodes & Pfaeffli, 2010). This have led to the development of models that integrate multiple behavioral theories and predictors to examine the processes that explain what influences PA behavior. An example

of such a model is the Integrated Model of Behavioral Change (Hagger & Chatzisarantis, 2014) which goes beyond explicitly intentional (i.e., theory of planned behavior) and motivational (i.e., self-determination theory) considerations.

Interventions in nursing homes for PwD are much more complex, as motivational and volitional processes are less relevant to the performance and maintenance of PA. Therefore, a more comprehensive approach is needed for this context, which still allows for an integration of theories and models, but also takes more into account the environment and the surrounding context. In general, all the theories and models mentioned above can be criticized for not taking the environment sufficiently into account. In response to this criticism, social-ecological models of health behavior have been developed in recent years, which emphasize both individual influences and social, political and environmental factors (Stokols, 2000). This approach assumes that behavior is influenced at multiple levels and that these need to be addressed equally for sustainable change. The benefits of the ecological perspective for health research have been recognized and discussed (McLaren & Hawe, 2005; Stokols, 2000), but have not yet been fully integrated.

2.3.2.2 Intervention planning incorporating theory- and evidence-based knowledge

Health behaviour is influenced at multiple levels. Social-ecological approaches are increasingly used in health interventions, including those related to PA (Buchan et al., 2012). These approaches view health as a function of both the individual and the environment in which the individual lives, including the family, social networks, organisations, communities and societies (Kok et al., 2008). Interventions are events that target specific changes in behaviour or environment within a system. Other factors within a system can influence the effect of the intervention by strengthening or weakening the effect on the specific behavioural or environmental change targeted (Kok et al., 2017). In particular, when interventions affect behaviour and the environment at multiple levels, they are referred to as complex interventions. Research on complex interventions is broad in scope and needs to answer questions that go well beyond achieving the intended outcomes, as described in the Medical Research Council guidelines for the development and evaluation of complex interventions (Skivington et al., 2021). These include questions about identifying the added value and assessing its value in relation to the resources needed to deliver it, but also questions about implementation, integration and interaction, how the intervention contributes to systems change, or how the results can influence decision-making in the real world (Skivington et al., 2021).

In general, most health problems are multidimensional, meaning that action must be taken at the individual, organizational, community, and societal levels to address the problem (Kok et al., 2008). Developing effective health promotion interventions requires a number of steps,

including reviewing relevant literature, applying theory, gathering new data, and involving experts and stakeholders in the planning process (Fernandez et al., 2019). Using information from these diverse sources to support intervention development can be challenging, even for well-trained health promoters (Fernandez et al., 2019). Although systematic intervention planning is widely used in health promotion, there is a serious lack of programs and interventions that integrate behavior change theories, particularly in the context of secondary and tertiary prevention (Karloh et al., 2023). However, the correct application of behavior change theories is critical to improving adherence and promoting positive outcomes.

The most commonly used framework for the planning and designing of interventions in a health context is the IMF (Bartholomew Eldredge et al., 2016). The basis of the IMF is the socio-ecological model, which focuses on the interrelationships between individuals (biological, psychological and behavioral characteristics) and their environment (Bartholomew Eldredge et al., 2016). The IMF considers the target population, its environment and the people in that environment who can influence the target population (Svendsen et al., 2022). The aim of the IMF is both to facilitate stakeholder participation and consultation, and to provide a structure for integrating theory and findings from the empirical literature with information collected from the target population (Svendsen et al., 2022). The use of IMF has been shown to be effective in a number of different areas, such as prevention of occupational hazards, empowerment, and return to work (Bakhuys Roozeboom et al., 2021; Kok et al., 2017), as well as in a number of behavior change contexts and settings (both clinical and public health), including the promotion of PA in older people (van Stralen et al., 2009).

The IMF was developed in the field of health promotion in 1998. It consists of six iterative steps (described and applied in Chapter 4.2). These steps range from needs assessment to program design, as well as implementation and evaluation. Each step is broken down into specific tasks, all of which together result in a behavior change intervention that is adapted to a specific context and has the best chance of success (Kok et al., 2017). Within a step, the tasks create a product that determines and guides the process in the next step. However, the six steps are not to be understood linearly, but rather follow an iterative process (Bartholomew Eldredge et al., 2016; Kok et al., 2016). The process is also cumulative in that the foundation for one step is provided by the previous step, so missing a step may jeopardize or limit the potential effectiveness of the intervention (Bartholomew Eldredge et al., 2016). According to Bartholomew Eldredge et al. (Bartholomew Eldredge et al., 2016), intervention planning can typically be done backwards to include, repeat or deepen a previously neglected step.

The IMF consideres theories and supports the use of behavior change techniques based on a particular theory or model to address the specific determinants to achieve behavior change.

Taxonomies of behavior change techniques that have been developed to specify the content of behavior change interventions are also considered (Abraham & Michie, 2008; Michie et al., 2011). Conversely, the IMF has its own taxonomy describing behavior change methods that intervention designers can choose from depending on the circumstances. These behavior change methods are general techniques or processes that have been shown to change one or more determinants of behavior (e.g., self-efficacy) and are likely to influence behavior (Kok et al., 2016). There are currently well over 1,000 published articles using the framework (Fernandez et al., 2019). The IMF is also being used in the development digital health interventions.

2.3.3 Digital intervention planning based on the Intervention Mapping Framework

Digital interventions need to be carefully designed to ensure their impact on users and effectiveness (Jaffar et al., 2022). Although digital interventions, particularly mHealth applications, are becoming increasingly popular, there is limited evidence of their effectiveness (Marcolino et al., 2018), most likely due to the unmet requirement to involve users in the design process (Schnall et al., 2016). The challenge is that mHealth applications that are designed for users, but not with users, will result in high technology refusal rates (Matthew-Maich et al., 2016; Osborne et al., 2021). Furthermore, as with all interventions, context and influencing factors need to be taken into account the. Particularly in case of digital interventions, other relevant variables that can be traced back to the use, usability, and operability of digital solutions are critical to the subsequent success of the intervention. Therefore, an iterative development process that includes observing users' interaction with the application is very important (Witteman et al., 2021).

The IMF is a way of delivering complex interventions (Skivington et al., 2021) and offers the opportunity to take a user-centered approach. This has been shown to be very important for people with chronic conditions, as highlighted in a review focusing on unmet care needs related to their physical and mental health, social life and the environment in which they live and interact (Abdi et al., 2019). User-centeredness is also of great interest with regard to the interface between technology and humans. In this context, User Experience Research (UX) is a discipline that analyses the behavior, motivation and needs of users in order to improve the design of technical products, services and software (Luther et al., 2020). UX research is based on different theories and methods. In the case of digital interventions, the impact and effectiveness of the intervention directly depends on the usability of the digital solutions. Therefore, theories, behavioral change techniques and UX research need to be considered to determine the most effective intervention.

A systematic review of the Pubmed and Scopus databases was conducted to obtain an overview of the use of IMF in the design and development of digital health interventions. The aim was to focus on digital health interventions that focus on or integrate PA and exercise (see Annex A for search terms and further details). After removing duplicates, 633 hits were identified. After analyzing the titles and abstracts, 74 articles were identified that used IMF to develop a digital intervention. The topics and application areas were broad, ranging from monitoring with targeted feedback on health-related behaviors such as eating habits (Hallsworth et al., 2021) or smoking cessation (van Agteren et al., 2018), to support for specific diseases such as diabetes (Hadjiconstantinou et al., 2020), cardiovascular disease (Engelen et al., 2020) or rheumatoid arthritis (Zuidema et al., 2019), to game-based therapy for children with disabilities (Johnson et al., 2022) or sexual education to prevent unwanted pregnancy (McCarthy et al., 2018) or HIV infection (D. H. Li et al., 2020). Studies that addressed the promotion of PA, or integrated it into the intervention, were included in the final qualitative analysis by analyzing the aims and content of the digital interventions. The 21 studies included in this systematic review and the findings on the aim, setting, form of digital intervention, integration of PA and exercise content and theoretical underpinning are shown in Table 2.2. Within the table, the theoretical underpinnings as well as the integration of UX methods and the application of iterative user-centered digital development processes were extracted from the full texts and qualitatively summarized.

Table 2.2: Qualitative analysis of 21 studies identified by literature review

Reference	Aim / health issue	Setting / target group	Form of digital intervention	Health promotion or prevention and theoretical foundation	Integration of user participation as well as known methods or theories
(Berry et al., 2023)	PA-promotion by motivation, self-efficacy, sustained engagement	People with Osteoarthritis	Website intervention	Secondary or tertiary prevention, BCT Taxonomy (Michie et al., 2013)	Within Step 4: Digital prototype development, usability testing (think-aloud sessions), acceptability testing (in-depth interviews); Novel use of the Theoretical Framework of Acceptability
(Blacket et al., 2024)	Improvement of running-retention in new runners	Novice and returning runners	Website intervention	Health promotion and primary prevention; practical Behavior Change Wheel (BCW) and BCT Taxonomy (Michie et al., 2011)	Within Step 1: Interviews with end-user, expert consultation; Pre-tests using a purpose-built feedback questionnaire based on established UX research and recommendations (Schrepp, 2023)
(Boekhout et al., 2017)	PA-promotion and social network	Single, one or more chronic disease; > 65 years,	Computer-tailored eHealth intervention	Secondary or tertiary prevention; I-Change Model (de Vries et al., 2003).	Within Step 3: Focus group questionnaires; no theories mentioned
(Busse et al., 2021)	PA-promotion	People with progressive multiple sclerosis	Website intervention, multiuser system	Secondary or tertiary prevention; No mentioned theoretical foundation	Step 1: structured interviews of potential end-users, their families/carers and healthcare professionals; no theories mentioned
(Y. Chen et al., 2019)	PA-promotion and healthy diet	People with coronary heart disease	Mobile health intervention	Secondary or tertiary prevention; Contemplation-Action-Maintenance behavior change model (Yue et al., 2021)	Within Step 1: assessing needs relevant to presentation modes and to functional features of the application; no theories mentioned
(Den Bakker et al., 2019)	PA-promotion to achieve earlier recovery	People after general surgical and gynecological procedures	Mobile health intervention, active tracker	Secondary prevention; Attitude-Social Influence-Self-Efficacy model	Within Step 2: process evaluation, survey study to investigate i.e., whether eHealth may be of assistance, focus group discussion to evaluate i.e., possible solutions for unmet needs; no theories mentioned
(Direito et al., 2018)	PA-promotion, sedentary behavior reduction	Entire population	Mobile health intervention	Health promotion, primary prevention; Theory of planned behavior and self-determination theory	Within Step 4: BIT

(Engelen et al., 2020)	Self-management on PA-promotion	People with cardiovascular disease	Web-based self-management intervention	Secondary or tertiary prevention; no mentioned underlying theory	Within Step 6: process evaluation for insight into the working elements of the program, patient needs in eHealth, and the use of the program by patients; no theories mentioned
(Golsteijn et al., 2017)	PA-promotion	People with prostate and colorectal cancer	Computer-tailored eHealth intervention	Secondary or tertiary prevention; I-Change Model, Health Action Process Approach, theories of self-regulation, and the Precaution Adoption Process Model	Within Step 1: interviews with end-users and health professionals; within Step 4: data of process evaluation of the basic intervention was used for further adaptations; within Step 6: feasibility study; no theories mentioned
(Hallsworth et al., 2021)	PA-promotion and healthy diet, weight loss	People with nonalcoholic fatty liver disease	Digital intervention	Secondary or tertiary prevention; Theoretical Domains Framework	Within step 4: interactive group workshops to identify issues related to acceptability and usability; within Step 6: piloting for data on access, usability, and content; no theories mentioned
(Jaffar et al., 2022)	Improving pelvic floor muscle to reduce urinary incontinence	Pregnant women	Mobile health intervention	Primary and secondary prevention; the social cognitive theory, the health belief model, and capability, opportunity, and motivation-behavior	Within Step 4: software development lifecycle by five focus group discussions; user-centered design-11 checklist; mHealth development and evaluation framework
(Latrille et al., 2023)	PA-promotion	People with obstructive sleep apnea	Mobile health intervention	Secondary and tertiary prevention; multiprocess action control and Health Action Process Approach model	No description of the development process; no theories mentioned
(Lobo et al., 2023)	Hypertension management	People with hypertension	Mobile health intervention, wearable blood pressure device	Primary and secondary prevention; information, motivation, and behavior skills model and the patient health engagement model	Within Step 2: needs prioritization ed by MoSCoW; Within Step 3: implementation of theoretical and practical strategies in consultation with stakeholders; within Step 4: identification of the functionality; no theories mentioned
(Palacz-Poborczyk et al., 2022)	Weight loss, identification of modifiable predictors	People with excess body weight	Digital intervention	Secondary and tertiary prevention; no mentioned underlying theory	Within Step 4: focus groups framed as user engagement workshops and interviews; no theories mentioned

(Plaete et al., 2015)	PA-promotion and fruit and vegetable intake	Entire population	Digital intervention	Health promotion; health action process approach model, and taxonomy and list of (Abraham & Michie, 2008; Bartholomew Eldredge et al., 2016)	Within Step 4: pretest to identify possible elements of improvement and to evaluate feasibility and user-friendliness; retrospective test of feasibility, acceptability, and user-friendliness
(Potzel et al., 2021)	Change of cardiometabolic risk behaviors	Women during the first five years post-gestational diabetes mellitus	Mobile health intervention	Primary prevention; social-ecological model, automatic behavior and habits, goal setting, information processing/persuasive communication, process models of behavior change, and social cognitive models	Within Step 4: user tests, 2 test rounds with end users, mixed methods design on user acceptance; development in cooperation with industrial partners to ensure a high technological standard, based on iOS developer human interface guidelines
(Puijk-Hekman et al., 2017)	Change and self-management of behavioral and metabolic risks	People with cardiovascular diseases	Web-based intervention	Secondary prevention; Integrated Change Model 2.0 for change objectives, Coding Manual for BCT for selection of methods,	Within Step 4: pretests; Within Step 5: Focus group discussions on dissemination and exposure; no theories mentioned
(Sanders et al., 2023)	PA-promotion, increase daily PA and short bouts of PA	Inactive adults	Mobile health intervention, wearable technology	Health promotion; control theory (Carver & Scheier, 1982), self-regulation behavior theory (Kanfer & Gaelick-Buys, 1991), BCT taxonomy (Michie et al., 2013)	Within Step 4: app development with company; within Step 1: public respond (n=165) to a questionnaire regarding app-concept and use of digital technology for behavior change; focus group discussions and survey (n=754) on app concept and features, and experiences on PA-tracking tools; within Step 3: needs prioritization by MoSCoW; within Step 4: user testing (user engagement and user version of the mobile application rating scale (uMARS) (Stoyanov et al., 2016); UX techniques in the design of the app
(Sassen et al., 2012)	PA-promotion, improve cardiovascular risk factors	Health professionals and patients with cardiovascular risk factors	Web-based intervention	Primary and secondary prevention; no explicit theory as foundation was mentioned, several theory-based methods were selected and described	Within Step 1: focus group interviews; within Step 4: tests and interviews with experts and end users; no theories mentioned

(Svendsen et al., 2022)	Self-management low back pain, reduce pain-related disability	People with nonspecific low back pain	Mobile health intervention	Primary and secondary prevention; behavior change theory and normalization process theory; core process as underlying method	Stakeholders and target group involvement, user testing, feasibility studies and a pilot study; within Step 1: interdisciplinary planning group, needs assessment out of user perspective; Within Step 4: content production with brainstorming and workshops, testing, and refinement, creation of personas, within Step 5: normalization process theory to identify determinants of adoption and implementation; user interface with consideration of Apple Human Interface Guidelines, Apple Research Kit, and Google's Material Design
(Zuidema et al., 2015)	Self-management on health behavior	People with rheumatoid arthritis	Computer-tailored intervention	Secondary and tertiary prevention; no mentioned underlying theory; methods based on BCT	Within Step 1 to every step of development process: active patient participation by integrating a multidisciplinary panel; within Step 4: cooperation with an information and communications technology partner, testing with mixed-methods; no theories mentioned

BIT = behavioral intention technology; BCT = behavior change technique; IMF = Intervention Mapping Framework; MoSCoW = Must have, Should have, Could have, Won't have, PA = physical activity; SB = sedentary behavior; details on the six steps of IMF are presented in Chapter 4.2

The qualitative analysis of the articles on digital interventions developed using IMF shows that the methods used in terms of user-centeredness, human-technology interaction considerations and the technical implementation are very diverse. Although the numerous references to the use of IMF in the field of digital intervention planning show that it is a promising approach, however there is no proven system for integrating UX methods or applying user-centeredness in a technical sense.

2.3.4 Summary of theory- and evidence-based intervention planning

In summary, digitalization offers great potential for the delivery of PA and exercise-related interventions, especially for older people, but also for people with disease, to counteract age- and disease-related decline. The development of digital interventions requires approaches that incorporate both theory and evidence, as well as environmental conditions that influence implementation. IMF provides such a framework for complex interventions. The application examples show that IMF has been widely used in the development of digital interventions, including in the context of exercise interventions or intervention content movement. The user-centered nature but also the special consideration of the environment and the social context of this approach allows it to be easily applied in the context of digital intervention planning. However, there is currently no proven method for integrating UX methods or applying user-centeredness in a technical sense.

3 Research question and objectives

The research question and the objectives of this habilitation thesis are derived from the current state of research and the relevance for the non-pharmacological treatment of PwD. To this end, Chapter 3.1 summarizes the research deficits based on the theoretical part of this habilitation thesis. These deficits are related to known challenges regarding the target group of PwD in nursing homes as well as the context of app development. Based on this, the research question, and the research objectives related to the respective research area are formulated in Chapter 3.2.

3.1 Summary of research deficits

Given the demographic changes described above and the associated increase in the number of PwD, interventions that can be integrated into the daily routine of nursing homes are essential. Exercise interventions are a promising non-pharmacological treatment for PwD. However, there is a lack of conclusive evidence on the effects of PA, partly due to the variety of exercise combinations, delivery methods and challenges posed by different individual and environmental determinants. There is a lack of studies that take into account the heterogeneity of PwD in nursing homes. In addition, there are challenges related to the assessment of physical performance, in particular the lack of assessment methods developed specifically for PwD, the general measurability of this sample, and the lack of educational guidelines for instructing and monitoring exercises within this sample. From a technical point of view, there are challenges in implementing a digital solution due to the low level of technical equipment in the nursing homes or the low level of technical acceptance or experience of the NHE.

The research deficits can be summarized as follows:

- Deficits in exercise interventions with conclusive evidence on the effects of PA and exercise in PwD.
- Deficits in the measurability of physical performance in PwD.
- Deficits in adequately addressing the educational challenges of managing and monitoring PA in PwD.
- Deficits in theory- and evidence-based approaches that take into account important individual and environmental determinants.

- Deficits in addressing the heterogeneity of cognitive and physical performance of PwD in nursing homes.
- Deficits in implementable exercise interventions that can be used in nursing homes under the guidance of the NHE.

These deficits can be attributed to two main areas of research from which the research question and objectives are derived. These areas are (1) the effects of exercise on age- and disease-related cognitive and physical decline in PwD in nursing homes, (2) the planning and design of digital exercise interventions taking into account key determinants. Currently, there are no digitally implementable, theory- and evidence-based exercise interventions for PwD in nursing homes that can be used by NHE.

3.2 Derivation of research question and objectives

The research question can be derived from the relevance of the topic in relation to the research deficits which are summarized in Chapter 3.1. Based on these research deficits, the following research question is formulated:

How can a theory- and evidence-based digital exercise intervention be planned and designed to enable nursing home employees to provide individualized exercise to PwD to counteract age- and disease-related decline?

To answer this research question, objectives are defined along the two main research areas derived from the research deficits in Chapter 3.1. These objectives are specified in Table 3.1 with reference to the respective evaluation level.

Table 3.1: Overview of the objectives within the two main research areas with reference to the respective evaluation level

	Effects of exercise on age- and disease-related cognitive and physical decline in PwD	**Planning and design of a digital exercise intervention considering key determinants**
Overall objective	The objective is to provide a digital exercise intervention for PwD, applicable to NHE, that counteracts the age- and disease-related cognitive and physical decline.	
Planning evaluation	The objective is to provide • an overview of age-related decline in physical performance and to describe the impact of PA; • an overview of PA behaviors in nursing homes and the potential of digital solutions to promote PA; • evidence on the effects of a group-based multimodal exercise intervention on the physical and cognitive performance in PwD.	
Structure evaluation	The objective is to investigate • the psychometric properties of physical performance tests in PwD; • an individualization approach based on the physical and cognitive performance of PwD.	The objective is to investigate • the end-users i.e., NHE, to identify the requirements and prerequisites of the digital exercise intervention; • the application development process from a sports science point of view and to define the role of sports scientists in the development process.
Process evaluation		The objective is to define and apply • a theory- and evidence-based digital exercise intervention design to develop a digital exercise intervention; • a user-centered iterative application development process, by integrating feedback loops; • the dementia-specific multimodal exercises that can be digitally delivered by NHE.
Outcome evaluation	The objective is to examine the usability and effectiveness of the digital exercise intervention applied in nursing homes.	
Outlook	The objective is to investigate further digital and technological solutions • e.g., virtual reality, to expand the range of treatment options and assess their feasibility for PwD; • e.g., exoskeletons, to improve the assessment of physical performance and define support for age-related limitations.	

In order to achieve the overall objective and answer the research question, objectives could be defined that represent sub-steps in the planning, design and development of the digital exercise intervention. Key objectives have been addressed in the study InCoPE (Individualized Cognitive and Physical Performance). The IMF was used to address the objective of a theory- and evidence-based intervention planning and design. The integration of the objectives and the application of the IMF are described in detail in the following chapter.

4 Methods

Based on the theoretical foundations (see Chapter 2), the summarized research deficits (see Chapter 3.1) and the objectives of this habilitation thesis (see Chapter 3.2), the digital exercise intervention was developed using the IMF as the methodological basis. Chapter 4.1 describes the overall methodological approach with the interrelations and contributions of the research articles to the theory- and evidence-based planning and design of the digital exercise intervention. The application of the six steps of the IMF based on the research articles is presented in Chapter 4.2. Chapter 4.3 describes the methodological details of each of the studies underlying the research articles.

4.1 Overall consideration of the methodological approach

The overarching methodological framework of this habilitation thesis is based on the IMF. The combination and application of multiple theories and methods, as well as integrated implementation and evaluation planning, are part of the IMF (Bartholomew Eldredge et al., 2016). IMF includes steps such as needs assessment, program design and implementation in a comprehensive approach to planning theory- and evidence-based interventions (Bartholomew Eldredge et al., 2016). It takes into account criticisms of purely behavioral interventions, namely that behavioral change approaches often fail in existing networks due to their individual behavioral change approaches and also incorporates evidence from implementation science (Hagger & Weed, 2019; Kok et al., 2017). The IMF consists of six steps that have been successfully applied in the InCoPE-App. The interrelated research articles contribute to the planning and design of the theory- and evidence-based digital exercise intervention. The integration of the research articles is shown in Figure 4.1.

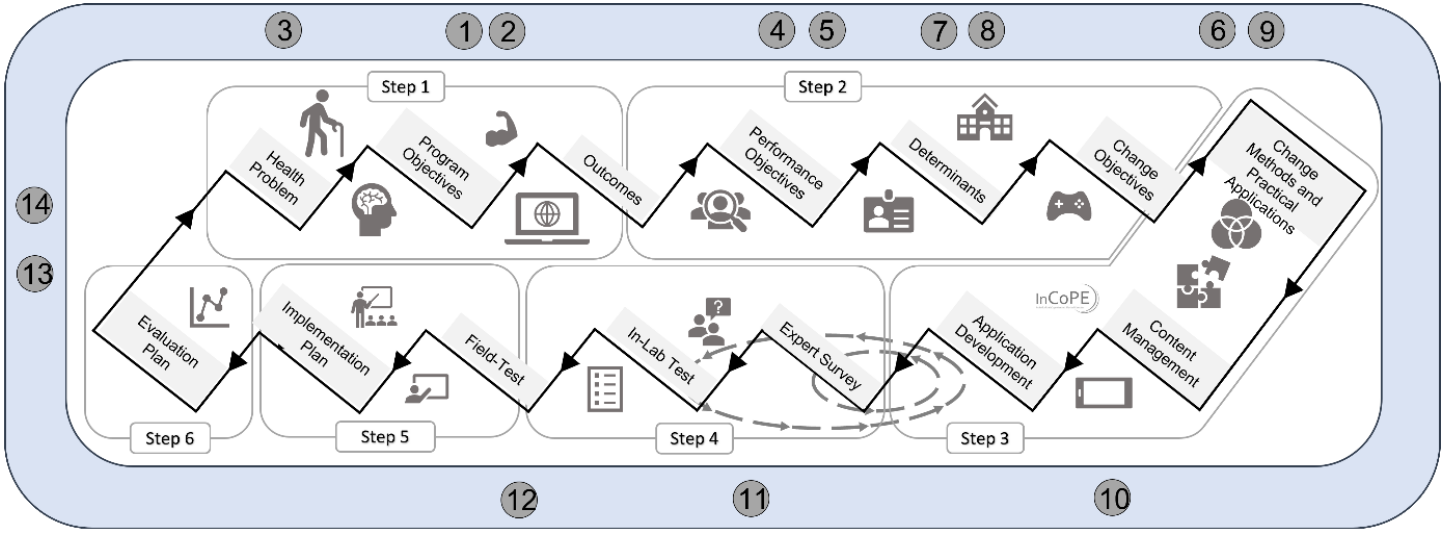

Figure 4.1: The six steps of the Intervention Mapping Framework applied on the design of the digital exercise interven-tion with relation to the research articles (1-14)

The research articles that address the objectives based on the identified research deficits are listed in Table 4.1. In addition, the areas to which the research contributions and findings relate and the specific research objectives are presented.

Table 4.1: Research articles of the habilitation thesis to address the research objectives

No	Reference	Contributions	Research objective
1	(Barisch-Fritz, Trautwein et al., 2022)	Effects of PA, exercise science	To evaluate the effects of a group-based exercise intervention for PwD living in nursing homes.
2	(Barisch-Fritz, Shah et al., 2025)	Effects of PA, exercise science	To investigate the effects of an exercise intervention on cognitive performance in PwD and to determine a methodological approach based on machine learning for the analysis of RCTs to identify possible predictors for cognitive decline.
3	(Barisch-Fritz et al., accepted)	Effects of PA, exercise science	To provide an overview of age-related decline in physical performance and describe the impact of PA on age-related decline.
4	(Trautwein, Maurus et al., 2019)	Assessment of physical performance, effects of PA, exercise science	To investigate the psychometric properties of physical assessments in PwD.
5	(Barisch-Fritz, Krafft et al., 2025)	Assessment of physical performance, effects of PA, exercise science	To examine the reliability of physical performance tests adapted for PwD.
6	(Barisch-Fritz, Bezold et al., 2023)	Exercise science	To investigate the cognitive and physical performance of PwD and identify an approach for the individualization of PA and exercise interventions.
7	(Barisch-Fritz et al., 2020)	Digital intervention planning, UX research	To define the sample of the end-users and prepare information about them for software engineers.
8	(Barisch-Fritz, Krafft et al., 2023)	Digital intervention planning, UX research	To analyze the affinity for technology and technology interaction among NHE.
9	(Barisch-Fritz, Nigg et al., 2023)	Digital intervention planning, sports science and education of sports scientists	To examine the app development process from a sports science perspective.
10	(Barisch-Fritz, Bezold, Scharpf et al., 2022b)	Digital intervention planning, UX and implementation research	To identify the user-centered iterative evaluation process for application development.
11	(Krafft et al., 2023)	Digital intervention planning, adult education, behavioral science, and nursing science	To investigate the end-users' feedback on the usability of a digital application.
12	(Barisch-Fritz, Bezold, Scharpf et al., 2022a)	Effects of PA and digital intervention planning	To examine the usability and effectiveness of the digital exercise intervention used in nursing homes.
13	(Prinz et al., 2024)	Effects of PA and digital intervention planning	To use other digital tools, such as virtual reality, to extend the range of treatment options and assess their feasibility for PwD.
14	(Möller et al., 2025)	Assessment of physical performance	To investigate the use of assistive digital solutions such as exoskeletons to improve physical assessment and define support for age-related limitations.

Based on the research articles listed in Table 4.1, as well as other articles produced as part of the project, the following chapter explains how the six steps of the IMF were applied in relation to the design and development of the digital exercise intervention. It is important to recognize that the IMF is an iterative and at the same time cumulative approach, i.e., it is necessary to go through and refine the steps several times. It should therefore be seen as a framework for continuous improvement that does not anticipate the failure of an intervention, but always offers the possibility of improvement based on lessons learned.

4.2 Application of the steps of Intervention Mapping Framework

4.2.1 Step 1 of the Intervention Mapping Framework: Logic Model of the Problem

The logic model of the problem is the starting point for Step 1 of the IMF. It was developed in relation to the age- and disease-related decline in cognitive and physical performance of PwD in the nursing home setting. Figure 4.2 shows this logic model of the problem, which is based on the PRECEDE model (Green & Kreuter, 2005). It illustrates the starting point for the need for interventions that consider and integrate different determinants, which is of great importance in the context of care dependency.

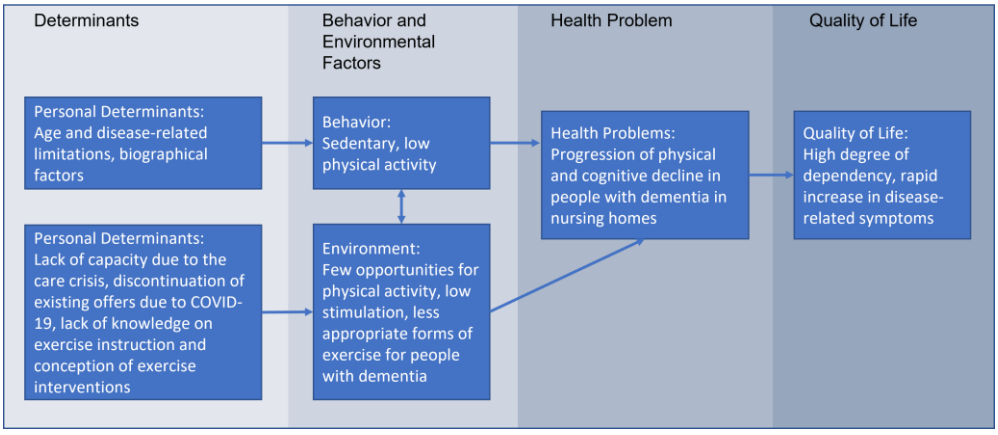

Figure 4.2: Logic model of the problem

The logic model relates the PA behavior or situation of people with cognitive impairment and/or dementia, which is determined by the age- and disease-related changes, to the environmental determinants, which in this case are largely determined by the specific characteristics and conditions of the nursing home setting. Many aspects underlying this logic model are described in the theoretical part, including the PA behavior of PwD, the relationship between PA and age- and disease-related decline in physical and cognitive performance (Chapters 2.2.2 and 2.2.3), and the specifics of exercise interventions and assessment for PwD and conditions in nursing homes (Chapter 2.2.4).

At this level of planning, a randomized controlled clinical trial was conducted to provide valuable evidence to support the logic model of the problem and the underlying needs assessment. The effects of the group-based multimodal exercise program were evaluated in 319 PwD living in nursing homes. The effects on physical performance (Barisch-Fritz, Trautwein et al., 2022), ADL (Bezold et al., 2021), and cognitive performance (Barisch-Fritz, Shah et al., 2025) were analyzed. In addition, the age-related decline in physical performance and the effects of PA have been elaborated (Barisch-Fritz et al., accepted) and have contributed significantly to the derivation and definition of the program objectives and outcomes.

4.2.2 Step 2 of the Intervention Mapping Framework: Logic Model of Change

Although the determinants are already visible in Step 1, Step 2 is about translating the behavior determinants into objectives. This is done on the basis of the findings from Step 1 and leads to the definition of the logic model of change. The logic model of change, shown in Figure 4.3, describes the performance objectives of the intervention taking into account the determinants in both the individual and social context.

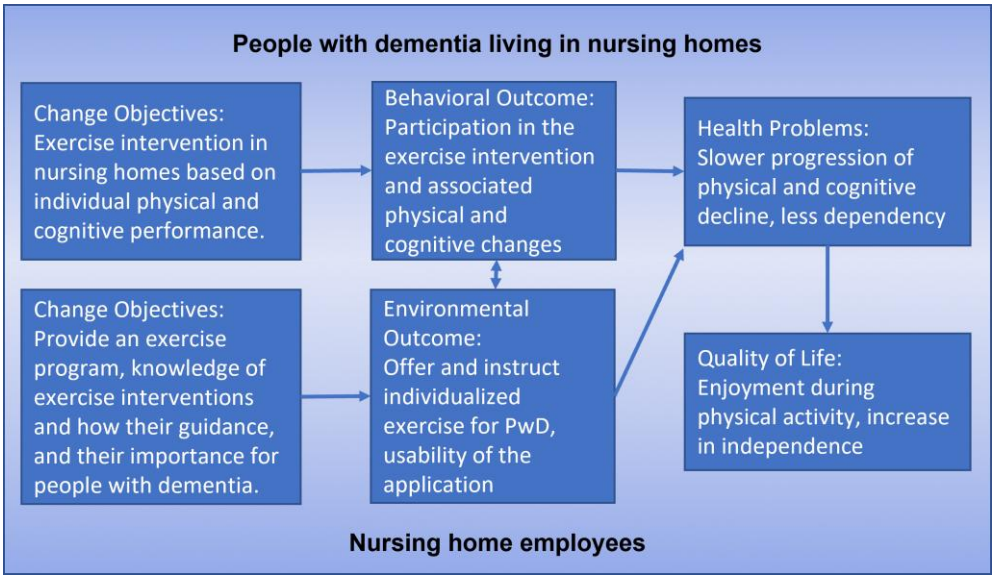

Figure 4.3: Logic model of change

This logic model of change attempts to describe the areas in which change, and outcomes are sought, taking into account their interrelations. Starting from the health problem, which has an undeniable impact on the quality of life, the behavior change of the PwD includes participation in the exercise intervention and, as a result, associated physical and cognitive changes. Therefore, the aim of the change is to adapt the exercise program to the needs and physical and cognitive preconditions of PwD. On the part of nursing home and the NHE, the result is to create opportunities for the application and instruction of an individualized exercise program. Therefore, the change objective at this level is to prepare an individualized exercise program in such a way that it can be instructed and integrated by the NHE.

Several determinants are relevant for the design of the digital exercise intervention, which were considered from a structural perspective. The transition from Step 1 to Step 2 was accompanied by an interdisciplinary perspective on digital solutions to promote PA in nursing homes (Möller et al., 2025). The central importance of the NHE is evident in several ways, especially in the design of the InCoPE-App, where they are involved as end-users. Thus, the analysis of the technology affinity and technology interaction of NHE was carried out by means of a Germany-wide online survey (Barisch-Fritz, Krafft et al., 2023). A more detailed description of the end-users was provided by the results of a stakeholder analysis, which aimed to explain the target group to the developers of the app and to highlight key points for user-centered development using UX methods (Barisch-Fritz et al., 2020). To this end, the

requirements for initiating and supporting the software development process in the context of the development of the digital application had to be addressed from a sports science perspective. Therefore, a literature review and an exemplary survey were conducted to define the requirements as well as the roles within sport science (Barisch-Fritz, Nigg et al., 2023).

Other challenges related to the outcomes, but also general measurability of PwD (see Chapter 2.2.4), concern the physical performance outcomes. A prerequisite for the assessment of physical performance was the selection of appropriate assessment methods (Trautwein, Barisch-Fritz et al., 2019) and the consideration of the psychometric properties. The psychometric properties of physical performance assessments were analyzed in a systematic literature review (Trautwein, Maurus et al., 2019). In a subsequent reliability study, adaptations of physical performance assessments were made, and their reliability was examined (Barisch-Fritz, Krafft et al., 2025). In view of the results of the RCT and the aim to increase intervention effects, an individualization approach applicable in nursing homes was defined. A cluster analysis based on the physical and cognitive performance data from the RCT data was used to identify training clusters (Barisch-Fritz, Bezold et al., 2023) and thus individualize the content.

4.2.3 Step 3 of the Intervention Mapping Framework: Program Design

Based on the logic model of change, the program idea was specified in Step 3 and the change methods and practical applications were integrated (Bartholomew Eldredge et al., 2016). The theory- and evidence-based change methods were to provide a digital application for NHE to test and train the physical and cognitive performance of PwD without specific sports science knowledge. This change methods correspond to the objectives of the intervention as shown in Table 4.2. The specific methods for the InCoPE-App were defined on the basis of theory- and evidence-based knowledge from two main scientific disciplines (1) Exercise science to generate effects of PA in PwD and (2) UX research to ensure the usability of the InCoPE-App, as the intervention and thus the success of the intervention directly depends on it.

Table 4.2: Objectives, methods and practical applications at the individual and inter-individual levels

Level	Change objective	Performance objective	Methods	Applications
Individual	Participation in tests to determine cognitive and physical performance and individual exercise inter-vention.	PwD participate in the digital exercise intervention	Information Persuasive communication	Information about the intervention for nursing homes, NHE, participants and their legal guardians
		PwD have fun in conducting the exercises	Tailoring Individualization	Pedagogically prepared exercises adapted to the characteristics and severity of the cognitive impairment to appeal PwD
		PwD maintain or increase their physical and cognitive performance	Tailoring Skills training Guided Practice	Individualized exercises, training control through evidence from exercise science
Inter-personal (environmental)	Provide and apply an individualized exercise intervention with dementia-specific instruction of physical and cognitive exercises.	NHE use the InCoPE-App	Information Modelling Active learning Persuasive communication Facilitation	Training modules to increase knowledge about PA and effects of PA, the instruction of PA and the use the InCoPE-App
		NHE offer and guide the digital exercise intervention		
		NHE rate the usability of the InCoPE-App positively	Participation	User-centered iterative app-development

The practical applications were defined by evidence from exercise science on adaptability to physical stimuli and evidence on the plasticity of age-related decline (Barisch-Fritz et al., accepted). Other contexts, with a particular focus on cognitive decline, are presented in Chapter 2.1.2. The impact of PA in PwD is presented in Chapter 2.2.3 and was also used to define theory- and evidence-based methods of change and to adapt the content for the target group. These methods were translated into practical applications by defining appropriate exercises and tasks. Other definitions in the context of practical applications relate to the delivery methods in terms of defining the scope, frequency, duration and intensity of the training. For the general control of the training, but especially for the individualization of the training, it was decided to test the physical performance every three weeks. The results and experience from the RCT were used and adapted (Trautwein et al., 2017). The basis for the selection, preparation and contextualization of the exercises was provided by Scharpf's doctoral thesis (Scharpf, 2020). In addition, specific training modules were developed for NHE to increase their knowledge about the effects of PA and how to provide PA to PwD. Theory-based knowledge integrating the respective methods (see Chapter 2.3.2) was implemented in the exercise intervention and in the training modules for the NHE. The development of the specific exercise content and composition was based on the definition of training clusters (Barisch-Fritz, Bezold et al., 2023). These were used as a basis for the composition of the exercises, but also for pedagogical considerations, in particular taking into account the severity of the cognitive impairment. All these considerations were made at the level of the effectiveness of PA for PwD.

In order to develop a user-centered application with a high level of usability, findings from UX research were used. In a first step, the characteristics of the end-users were considered in a stakeholder analysis and prepared for the development process and the actual developers (Barisch-Fritz et al., 2020). Essential considerations in this context were made in the article on PA behavior in the nursing home context and the interdisciplinary perspectives on digital and technical solutions and possibilities (Möller et al., 2025). In addition, the affinity for technology and technology interaction of NHE was considered (Barisch-Fritz, Krafft et al., 2023), which is relevant for both the development and the implementation of the InCoPE-App.

4.2.4 Step 4 of the Intervention Mapping Framework: Program Production

The aim of Step 4 of the IMF is to refine the structure and organization of the intervention, develop plans for materials, and produce, pre-test, and refine the materials (Bartholomew Eldredge et al., 2016). The produced materials are a logical continuation of Steps 1-3, leading

to translation in terms of effective operationalization of methods and practical applications. For the development of the digital exercise intervention, the main development phase of the app started with this step, including the findings and considerations from the previous steps, particularly in relation to context and setting. During the development the focus had to be on the end-users of the digital exercise application. The InCoPE-App was developed to fulfil two main tasks: First, to test the cognitive and physical performance of PwD and second, to guide the individualized exercise program. In order to successfully complete this phase, it was particularly important to analyze the development of the app from a sport science perspective (Barisch-Fritz, Nigg et al., 2023) and define the roles within the project.

The change and performance objectives were integrated into the digital application. The development of the digital materials was based on findings and experiences of the tested exercises from the preceding RCT (Barisch-Fritz, Trautwein et al., 2022; Trautwein et al., 2017) and by evidence from exercise science (Chapter 2.2). The central innovation was the implementation of the individualization approach, which was integrated via a specific algorithm and accordingly includes the assignment of exercises to the correct training groups. In addition, a regular test reminder was implemented to ensure that the training content as well as the intensity and complexity of the tasks were adjusted.

In Step 4, the transformation and integration of the digital material and the adaptation to end-users with their specific characteristics and conditions through the nursing home setting was monitored by defining an iterative development process (Barisch-Fritz, Bezold, Scharpf et al., 2022b). This was to ensure that the goal of user-centeredness and an implementable application was achieved. Only a high level of usability, and therefore correct and appropriate use of the application, would achieve the desired intervention effects. The usability tests were carefully carried out using a mixed-methods approach. Initially through several internal cycles and test phases, then extended by expert feedback (Barisch-Fritz, Bezold, Barisch et al., 2022) and feedback from the NHE under laboratory conditions (Krafft et al., 2023). This iterative process is strongly linked to the goal of implementation and thus to the goals and tasks of step 5 of the IMF.

4.2.5 Step 5 of the Intervention Mapping Framework: Implementation Plan

The aim of Step 5 of the IMF is to develop an implementation plan (Bartholomew Eldredge et al., 2016). In general, the aim is to reach a larger proportion of the population and thus achieve a greater impact of the intervention is of great interest. Implementing an intervention requires the use of behavior change methods that aim to bring about behavior change

(Bartholomew Eldredge et al., 2016). Thus, the development of a digital application can be seen as a tool for implementation as it can help to bridge the gap between research and practice as described in the Interactive Systems Framework (Noonan et al., 2012). Therefore, methods and practical applications are crucial for implementation. However, the InCoPE-App aims to be part of care, and therefore treatment rather than acting as a health promotion program. This implies a direct dependence on treatment effects, which is a prerequisite for implementation in the healthcare pathway. In addition, the development of a digital intervention is not possible without considering different facets of implementation in the design and development of the digital application. Implementation and application development go hand in hand, with a focus is on both the end-users and the implementers who are important for the acceptance, implementation and maintenance of the intervention. In addition, technical requirements and constraints, such as technical equipment or affinity for technology, are relevant to both development and implementation.

Implementation was already considered at the stage of developing the needs assessment, which is in line with the exploration stage of implementation as defined by the National Implementation Research Network (Fixsen et al., 2005). Considerations of technical solutions to promote PA were considered from different perspectives and among other things, the importance and involvement of the NHE was emphasized (Möller et al., 2025). The determinants and the consideration of the structural conditions are essential factors that are relevant for the definition of the change objectives and determinants and for the development of an implementable application. This was done by considering the stakeholders (Barisch-Fritz et al., 2020) and their contexts (Barisch-Fritz, Krafft et al., 2023) as well as the circumstances of the application development (Barisch-Fritz, Nigg et al., 2023). Implementation considerations regarding the correct use and maintenance of the intervention by the end-user were considered and integrated much earlier, as these are relevant development parameters. Last but not least, the user-centered iterative development process with the collection and integration of end-user feedback (Krafft et al., 2023) is also in line with IMF recommendations to involve adopters and implementers before Step 5 (Bartholomew Eldredge et al., 2016).

4.2.6 Step 6 of the Intervention Mapping Framework: Evaluation Plan

Step 6 of the IMF involves developing an evaluation plan based on the previous steps. Research evaluation to determine efficacy (effects under controlled conditions) and effectiveness (effects in the 'real world') is essential to provide the correct scientific framework for an evidence-based intervention (Bartholomew Eldredge et al., 2016). Similarly, evaluation is an essential part of project management and can be used to provide feedback to improve the

intervention and make the best use of scarce resources (Fetterman et al., 2015; Patton & Campbell-Patton, 2021). In particular, aspects of utilization-focused evaluation (Patton & Campbell-Patton, 2021), UX research (Rubin & Chisnell, 2008), and project management (Kolhoff, 2022) were used to inform the evaluation plan.

The evaluation plan covers the whole project of the designing and planning of the InCoPE-App, starting from the planning level. At this level, the research articles listed in Step 1 were written, which contributed to the needs assessment and the definition of the main intervention objectives. At the structural evaluation level, the research articles listed in Step 2 were written to analyze the stakeholders (Barisch-Fritz et al., 2020), the measurement parameters (Trautwein, Maurus et al., 2019) and the application development environment (Barisch-Fritz, Nigg et al., 2023). These contributed significantly to the definition of the performance and change objectives. At the process evaluation level, the user-centered iterative development process was defined (Barisch-Fritz, Bezold, Scharpf et al., 2022b) and evaluated in the form of expert feedback (Barisch-Fritz, Bezold, Barisch et al., 2022) and end-user feedback (Krafft et al., 2023). The final evaluation of the effects is carried out under standardized conditions specified by the application and can therefore provide fundamental insights into the effects as well as the effectiveness. In addition, usability after 18 weeks of use was analyzed as a key outcome (Barisch-Fritz, Bezold, Scharpf et al., 2022a).

4.3 Methods of the research articles

The evaluation plan defines four evaluation phases of planning, structure, process, and outcome evaluation in which the research objectives listed in Chapter 3.2 were analyzed. These are listed in Table 4.3 together with the methods used to achieve the objectives and the respective contribution of each research article.

Table 4.3: Overview on the research methods

	Research article; Reference	Design	Sample	Analysis
Planning evaluation	1; (Barisch-Fritz, Trautwein et al., 2022)	Randomized controlled trial	319 PwD, mild to moderate dementia, older than 60 years, living in nursing homes, walking ability of at least 10 m	Effect analysis (ANOVA in intention-to-treat and per-protocol sample), responder analysis
	2; (Barisch-Fritz, Shah et al., 2025)	Randomized controlled trial	319 PwD (same sample as above)	Machine learning approach for classification of cognitive decline
	3; (Barisch-Fritz et al., accepted)	Overview, book chapter	-	-
Structure evaluation	4; (Trautwein, Maurus et al., 2019)	Systematic literature review	46 included RCTs with interventions based on physical performance assessment and 21 reliability studies assessing the effects of physical performance	Extraction of frequency of use, effect sizes, psychometric properties, and several influences
	5; (Barisch-Fritz, Krafft et al., 2025)	Reliability study	26 PwD, mild to moderate dementia, older than 60 years, living in nursing homes, walking ability of at least 10 m	Calculation of reliability measure
Structure evaluation	6; (Barisch-Fritz, Bezold et al., 2023)	Randomized controlled trial	230 PwD, baseline data on physical and cognitive performance collected as part of the RCT	Hierarchical cluster analysis with Ward's method
	7; (Barisch-Fritz et al., 2020)	Survey / Stake-holder analysis	15 NHE	Descriptive analysis, methods of UX Research
	8; (Barisch-Fritz, Krafft et al., 2023)	Online survey	200 NHE in Germany	Multiple regression analysis
	9; (Barisch-Fritz, Nigg et al., 2023)	Systematic literature review and online survey	21 included studies, twelve respondents from academia	Descriptive statistics, ANOVA for group differences
Process evaluation	10; (Barisch-Fritz, Bezold, Scharpf et al., 2022b)	Study protocol	-	-
	11; (Krafft et al., 2023)	Laboratory study / mixed methods approach	14 NHE	Mixed method analysis

	Research article; Reference	Design	Sample	Analysis
Outcome evaluation and Outlook	12; (Barisch-Fritz, Bezold, Scharpf et al., 2022a)	Field study, usability study	10 NHE, 13 PwD, mild to moderate dementia, older than 65 years, walking ability of at least 10m	Usability analysis, case analysis
	13; (Prinz et al., 2024)	Feasibility study	33 PwD, MCI to moderate dementia, older than 65 years, walking ability of at least 10m	Pre-post analysis (paired t-test)
	14; (Möller et al., 2025)	Overview article	-	-

When analyzing the design and development process of the InCoPE-App, the study "Bewegung gegen Demenz" can be seen as a building block based on the planning evaluation. This study provided important and meaningful insights into the organization of exercise in nursing homes and group-based multimodal exercise interventions in a real-life setting. After randomization of PwD with mild to moderate dementia, aged 65 years and older, the intervention group exercised twice a week for 60 minutes with trained sports scientists using a prescribed multimodal exercise program. The control group maintained their usual routine and received standard therapy including exercise. At baseline and after the intervention, physical performance (i.e., mobility, balance, and lower extremity strength and function), cognitive performance (i.e., attention/ executive function, language, visuospatial skills, memory), and ADL were analyzed (Trautwein et al., 2017). In addition, baseline measures from the RCT of 230 PwD were used to exploratively identify an individualization approach based on cluster analysis of cognitive and physical performance data.

At the structural level, a systematic literature review was conducted in Pubmed, Web of Science, Cochrane Library, ALOIS, and Scopus (Trautwein, Maurus et al., 2019). Included were 46 RCTs that examined the effects of interventions on physical performance and 21 reliability studies on the measurability of physical performance in PwD. Results on frequency of use, effect sizes, psychometric properties, and also influence of severity and etiology of dementia and cueing were extracted. In a subsequent reliability study with 26 PwD with mild to moderate dementia, dementia-specific adaptations of the physical performance tests were made and then analyzed for reliability (Barisch-Fritz, Krafft et al., 2025). At this level, we also considered the end-users and their conditions and conducted a survey to characterize them in terms of a stakeholder analysis and integrated this into the considerations for the design of the mobile application (Barisch-Fritz et al., 2020). In addition, we conducted a nationwide online survey to which 200 employees of nursing homes in Germany responded. The online questionnaire included questions on socio-demographic variables, i.e., age, gender, occupational groups, education/degree level, two questionnaires on affinity for technology interaction and affinity for technology-electronic devices (Barisch-Fritz, Krafft et al., 2023). In addition, the context in which the app was developed was considered in a systematic review and an online survey of academic researchers focusing on the five main topics: development process, functional requirements and features, security, technology, and dissemination (Barisch-Fritz, Nigg et al., 2023). From the 21 included studies and the responses of twelve academic researchers, meaningful findings for the academic app development process were identified.

Based on the study protocol for the evaluation of the InCoPE-App, the user-centered and iterative development process was defined (Barisch-Fritz, Bezold, Scharpf et al., 2022b). The usability study was planned in several steps with the involvement of NHE as former end-users (Krafft et al., 2023). In a laboratory setting, NHE tested the InCoPE-App and provided

feedback on its use using a think aloud protocol, followed by completion of the System Usability Scale questionnaire. Findings from the think aloud transcripts were combined with findings from the questionnaire in a mixed methods approach to identify usability issues, and areas for improvement of the app.

The outcome evaluation was based on the effects within the PwD which were determined after the 18-week individualized digital exercise intervention (2 × 60 min/session) which was delivered to the intervention group by NHE using the InCoPE-App (Barisch-Fritz, Bezold, Scharpf et al., 2022a). Effects on cognitive (global cognitive function) and physical (balance, mobility, lower limb function and strength) performance were analyzed. In addition, the UX of the NHE was assessed using three usability questionnaires: PSSUQ and ISONORM 9241/110-S for usability, and AttrakDiff2 for pragmatic, hedonic quality-identity and stimulation, and attractiveness.

We see the possibility of Virtual Reality (VR) based exercise promotion for PwD as a potential further development regarding the integration of innovative technical solutions. To this end, we conducted a feasibility study on the use of VR for PwD (Prinz et al., 2024). The use of VR consisted of eight minutes with four scenes, each showing a park with different small impressions and presented as a 360° video. Cognitive (executive functions), physical (balance and mobility) and psychological parameters (emotions, mood, and fear of falling) were measured before and after immersive VR use. In relation to the issue of measurability of PwD, we see great potential in assistive technologies. Wearable robotic devices, such as exoskeletons, have the potential to assess physical performance over the duration of wear (Möller et al., 2025). In this review, we have considered established clinical and laboratory-based tests for assessing physical performance and discussed their transfer to exoskeleton-based procedures, as well as the feasibility and technological requirements and prerequisites for assessing human motor performance using lower extremity exoskeletons.

The results of the studies presented are summarized in Chapter 5.

5 Research articles

The results of this habilitations thesis comprise the research articles and are presented in four chapters related to the four evaluation levels. Chapter 5.1 summarizes the results at the level of planning evaluation, consisting of three research articles, and integrates their abstracts. Chapter 5.2 summarizes the results at the level of structural evaluation. It includes the abstracts and their classification of 6 research articles. Chapter 5.3 presents the results of the process evaluation, including the abstracts of two research articles. In Chapter 5.4, the results are presented at the level of the outcome evaluation and the outlook by integrating three abstracts of the research articles. The abstracts are taken from the original articles.

5.1 Effects of physical activity on age and disease-related decline – Planning evaluation of the digital exercise intervention

The aim within the first step of the IMF was to summarize the evidence on age- and disease-related decline in physical and cognitive performance. Consideration of the relationship with PA was highly relevant to the definition of the health problem, as well as to the program objectives and outcomes. Thus, the effects of a group-based multimodal exercise program on physical and cognitive outcomes were investigated in a RCT [research article 1 (Barisch-Fritz, Trautwein et al., 2022) and research article 2 (Barisch-Fritz, Shah et al., 2025)]. The general consideration of age-related decline and knowledge of the evidence for PA has been reviewed in a book chapter [research article 3 (Barisch-Fritz et al., accepted)].

The results of the RCT showed no statistically significant effects of the group-based multimodal exercise intervention on the physical performance of PwD (Barisch-Fritz, Trautwein et al., 2022). However, 28 % to 40 % of participants showed improvements in balance and lower limb strength and function. In addition, there was a high degree of heterogeneity within the target group and a dependence on the results of the initial physical performance level. PwD with lower baseline physical performance tended to benefit more than PwD with higher baseline physical performance. With regard to cognitive changes, a machine learning (ML) approach was used to identify predictors of decline or non-decline, of which adherence to the exercise intervention was an important component. The ML models showed moderate performance, suggesting that the selected variables made a limited contribution to the classification of cognitive decline. However, adherence to the exercise programme and ADL

performance (which also significantly determine the level of care required) were found to be important factors (Barisch-Fritz, Shah et al., 2025).

With regard to age-related physical decline, the effects of PA are well understood and have been discussed in the research article 3 (Barisch-Fritz et al., accepted) in relation to plasticity and the concept of healthy aging. PA and exercise in older adulthood are associated with a number of positive health outcomes, including reduced risk of mortality, cardiovascular disease, sarcopenia, cognitive impairment or neurodegenerative disease, and depressive disorders. In general, the ability to adapt to physical stimuli is maintained into old age, even in the presence of disease, which means that motor skills and abilities can also be improved in PwD through regular and targeted PA and exercise.

5.1.1 Research article 1: Effects of a multimodal exercise intervention on physical outcomes

Research Contribution

This research article can be categorized as a planning evaluation. It was designed to evaluate the effects of a group-based multimodal exercise intervention for PwD living in nursing homes. The article contributes to the effects of PA in general and adds to the knowledge of exercise science for PwD.

Reference

Barisch-Fritz, B., Trautwein, S., Scharpf, A., Krell-Roesch, J., Woll, A. (2022). Effects of a 16-week multimodal exercise program on physical performance in individuals with dementia: A multicenter randomized controlled trial. Journal of Geriatric Physical Therapy, 45 (1), 3–24. doi: 10.1519/JPT.0000000000000308.

Abstract

Background and purpose: Dementia affect physical as well as cognitive performance. In individuals with dementia (IWD), decline in physical performance increases with disease progression and is associated with higher functional dependence and decreased quality of life. It is paramount to examine factors that potentially preserve physical performance in IWD, particularly in light of conflicting findings on the effectiveness of exercise interventions on physical performance of IWD, mainly due to limited number of high-quality studies, large heterogeneity in methods used, or insufficient reporting of methods. The aim of this study was to investigate the effects of a 16-week multimodal exercise program (MEP) combining physical

and cognitive tasks on physical performance in IWD, and to identify individual characteristics of MEP responders.

Methods: A multicenter randomized controlled trial with assessment methods identified by an expert panel was conducted. We included 319 IWD of mild to moderate severity, older than 65 years, who underwent a standardized MEP specifically designed for IWD. At baseline and immediately after the MEP, we assessed physical performance (i.e., mobility, balance, and strength) and function of lower extremities (primary outcomes). Potential effects of the MEP on physical performance were identified using 2-factor analyses of variance with repeated measurements within 2 samples (i.e., intention-to-treat and per-protocol sample). Additionally, we compared characteristics related to physical performance between positive, non-, and negative responders.

Results and discussion: Neither analysis procedure revealed statistically significant time x group effects. However, 28 % to 40 % of participants were positive responders with regard to balance, and strength and function of lower extremities; and these persons had statistically significant lower baseline performance in the corresponding assessments.

Conclusions: This randomized controlled trial revealed no overall effects of the MEP on physical performance, probably due to high heterogeneity of the study sample. Findings in responder analysis showed that IWD with lower physical performance at baseline tended to benefit more than those with higher baseline performance. Thus, a higher degree of individualization of the MEP depending on baseline performance on IWD may improve overall MEP effectiveness.

Keywords

Cognitive impacts, dementia, motor impacts, physical activity, physical performance

Author Contribution

My contribution to this article was to plan, supervise and monitor the field study, prepare the data and carry out the analyses. I also initiated and wrote the article and was the corresponding author throughout the peer-review process.

5.1.2 Research article 2: Effects of a multimodal exercise intervention on cognitive outcomes

Research Contribution

At the level of the planning evaluation, this research article analyzed the cognitive decline and predictive variables for this decline within the RCT. This article contributes to the understanding of the impact of PA in influencing cognitive decline in PwD. It also provides an opportunity to examine changes within RCTs with heterogeneous samples using a ML approach.

Reference

Barisch-Fritz, B., Shah, J., Krafft, J., Geda, Y.E., Wu, T., Woll, A., Krell-Rösch, J. (2025). Physical activity and the outcome of cognitive trajectory: a machine learning approach. Eur Rev Aging Phys Act 22, 1. doi: 10.1186/s11556-024-00367-2.

Abstract

Background**:** Physical activity may have an impact on cognitive decline. Machine learning (ML) techniques are increasingly used in dementia research, e.g., for diagnosis and risk stratification. Less is known about the value of ML for predicting cognitive decline in persons with dementia (PwD). The aim of this study was to use an ML approach to identify variables associated with a multimodal exercise intervention that may impact cognitive changes in PwD.

Methods**:** This is a secondary, exploratory analysis using data from a RCT that included a 16-week multimodal exercise intervention for the intervention group (IG) and usual treatment for the control group (CG). Predictors included in the ML models were related to the intervention (e.g., adherence), physical performance (e.g., mobility and balance), and pertinent health-related variables (e.g., health status, dementia form and severity). Primary outcomes were global and domain-specific cognitive performance (i.e., attention/ executive function, language, visuospatial skills, memory) assessed by standardized tests. A Support Vector Machine model was used to classify each primary outcome into the two classes of decline and non-decline for CG and IG. GridSearchCV with 5-fold cross-validation was used for model training, and AUC and accuracy were calculated to assess model performance.

Results**:** The study sample consisted of 319 PwD (IG, N = 161; CG, N = 158). The proportion of PwD experiencing cognitive decline ranged from 27 to 48 % in CG, and from 23 to 49 % in IG, with no statistically significant differences and no time*group effects. ML models showed accuracy and AUC values ranging from 40.6 to 75.6. The strongest predictors of cognitive

decline or non-decline were performance of activities of daily living in IG and CG, and adherence and mobility in IG.

Conclusions**:** ML models showed moderate performance, suggesting that the selected variables only had limited value for classification, with adherence and performance of activities of daily living appearing to be predictors of cognitive decline. While the study provides preliminary evidence of the potential of ML approaches, larger studies are needed to confirm our observations and to include other variables in the prediction of cognitive decline, such as emotional health or biomarker abnormalities.

Keywords

Cognitive detoriation, influence on cognition, Alzheimer's disease, neurodegenerative diseases, exercise interventions, multimodal exercise program

Author Contribution

My contribution to the study was the design and supervision of the RCT and the data management. I also initiated, prepared, and wrote this article and was the corresponding author throughout the peer-review process.

5.1.3 Research article 3: Age-related physical decline and its relation to healthy aging and physical activity

Research Contribution

As part of the planning evaluation, this research article defines the health problem and the objectives and outcomes of the exercise program, focusing on age-related physical decline and the impact of PA on this decline. It contributes to exercise science with the aim by summarizing the knowledge of physical decline and the evidence for PA. It also helps to distinguish between age-related and disease-related decline, which is also relevant to the design of exercise interventions for the target group of PwD.

Reference

Barisch-Fritz, B., Woll., Mechling, H., Krell-Rösch, J. (accepted). Motorische Entwicklung und Mobilität im höheren Erwachsenenalter. In Niessner, Bös & Conzelmann (Hrsg.), Handbuch Motorische Entwicklung.

Summary of the book chapter

This book chapter describes the age-related decline in physical performance in older adulthood in terms of the motor skills of strength, endurance, balance, and mobility. The correlations of motor skills with parameters of physical and mental health in old age are also reviewed, as are the effectiveness of training and the plasticity of age-related physical decline. Many limitations in physical performance in later life are known, both in fine motor skills and in large motor skills such as walking. Age-related physical decline is strongly associated with the performance of ADL and thus with the maintenance of independence, but also with quality of life, increased risk of falls and mortality. The decline in motor skills is evident in all domains from middle age and is described in this chapter on the basis of current research into known causes and explanations, and the extent of the decline as a function of age and sex is discussed. The relationship between physical performance and healthy aging is also demonstrated by the association between declines in physical performance and various health outcomes, such as morbidity and mortality, functional capacity, and quality of life. Physical activity and exercise in older adulthood are generally associated with a range of positive health outcomes, including increased life expectancy and reduced risk of mortality, increased cardiorespiratory fitness and reduced risk of cardiovascular disease, improved skeletal muscle and reduced risk of falls and instability, improved cognitive performance and reduced risk of cognitive impairment or neurodegenerative disease, and increased well-being and reduced risk of depression and depressive disorders. In general, the ability to adapt to physical stimuli is maintained into old age, even in the presence of disease, which means that motor skills and abilities can also be learned and improved in this target group through regular and targeted physical activity and exercise. Knowledge of the high degree of adaptability and plasticity is relevant to the maintenance of physical performance and the targeted use of physical activity and exercise in older adulthood.

Keywords

Physical decline, motor performance, healthy aging, exercise, motor functioning

Author Contribution

My contribution to this book chapter was to research, describe physical decline and to write the manuscript in close collaboration with the other authors.

5.2 Determinants and change objectives for the exercise intervention for people with dementia in nursing homes – Structure evaluation for the digital exercise intervention

In this second step of the IMF, the determinants relevant to the planned intervention are identified and described. In addition, the change objectives and their dependencies on the determinants were considered in detail. With regard to the change objectives, we analyzed the reliability of physical performance tests in PwD, firstly in a systematic review [research article 4 (Trautwein, Maurus et al., 2019)] and secondly with regard to dementia-specific adaptations, which were examined in a field reliability study [research article 5 (Barisch-Fritz, Krafft et al., 2025)].

Based on the results of the RCT and the highly heterogeneous sample, we developed an individualization approach for the exercise intervention [research article 6 (Barisch-Fritz, Bezold et al., 2023)]. To make the application usable by NHE, we defined the methodology for designing the application and integrating relevant information from end-users [research article 7 (Barisch-Fritz et al., 2020)]. An important determinant for the instruction of a digital intervention by NHE is the technical affinity of the former end-user. This was investigated in the Germany-wide online survey [research article 8 (Barisch-Fritz, Krafft et al., 2023)]. From a more technical point of view, the application development process was evaluated from an academic perspective and in particular from a sports science perspective [research article 9 (Barisch-Fritz, Nigg et al., 2023)]. The aim was to look at application development and the roles involved from a sports science perspective in order to best guide and support development.

The main findings on the psychometric properties were that there was generally insufficient information on validity. Inter-rater and relative test-retest reliability was adequate, but absolute test-retest reliability was unacceptable for most assessments. Importantly, test-retest reliability is influenced by the severity and etiology of dementia and by cueing during the assessment. These influences suggest that assessments and instructions should be tailored to PwD (Trautwein, Maurus et al., 2019). As part of the reliability study (Barisch-Fritz, Krafft et al., 2025), adjustments were made to the instructions and scoring of the physical performance tests to take account for dementia-specific challenges. These adjustments did not improve the reliability values. However, this article has made an important contribution to the assessment of the absolute reliability of physical performance tests in PwD, which has been poorly performed due to a lack of information. In general, the results indicate the need for

further adaptations or tests specifically designed to assess physical performance in PwD in everyday situations.

In order to individualize exercise for PwD, four clusters were identified based on cognitive and physical performance data from 230 PwD. These four training clusters showed different characteristics that require the exercise program to be specifically defined, either in terms of the instruction and pedagogical preparation or in terms of the different content and intensity levels. These training clusters allow for more individualized exercise interventions and may lead to a greater effectiveness, especially in nursing homes (Barisch-Fritz, Bezold et al., 2023).

The broad approach to the design of the application was defined with a view to a better understanding of the future users (Barisch-Fritz et al., 2020). This was done by first describing the product vision followed by a stakeholder analysis based on a sample survey of 15 NHE. On this basis, four pseudo-personas could be described, which are characterized by their linguistic and technical knowledge, their experience, their needs, their behavior, their professional roles, and their own goals in the care context.

The affinity for technology and technology interaction among NHE is subject to different dependencies such as gender, age, and professional group. The cores of affinity for technology and technology interaction were lower among women, older participants, and nursing home managers. In general, we observed rather high values for affinity for technology and technology interaction, especially for NHE compared to managers. This is highly relevant with regard to the different perspectives of NHE and managers, who should be considered separately in the process of technological design, development, and implementation (Barisch-Fritz, Krafft et al., 2023).

The results of the systematic review and online survey indicate that there is a variable level of software engineering knowledge in the context of sports science app development. We also found that the role of sports scientists in app development is not well defined. The literature review revealed limited knowledge about the implementation of security measures, underlying technology, and dissemination. We present recommendations for improving the likelihood of success and sustainability of app development and provide guidance on the potential role of sports scientists as domain experts (Barisch-Fritz, Nigg et al., 2023).

5.2.1 Research article 4: Psychometric properties of physical performance tests in people with dementia

Research Contribution

At the level of structure evaluation, this research article reviews the psychometric properties of physical performance tests used in PwD through a systematic literature review. This article contributes to the understanding of physical outcomes in PwD and to the definition of change objectives by defining the changes that are both detectable and clinically relevant. As such, it makes a significant contribution to exercise science by providing knowledge on the reliability of physical performance tests in PwD, thus helping to assess the effects of PA.

Reference

Trautwein, S., Maurus, P., **Barisch-Fritz, B.**, Hadzic, A., Woll, A. (2019). Recommended motor assessments based on psychometric properties in individuals with dementia: A systematic review. European Review of Aging and Physical Activity, 3(16), 20. doi: 10.1186/s11556-019-0228-z.

Abstract

Background: Motor assessments are important to determine effectiveness of physical activity in individuals with dementia (IWD). However, inappropriate and non-standardised assessments without sound psychometric properties have been used. This systematic review aims to examine psychometric properties of motor assessments in IWD combined with frequency of use and effect sizes and to provide recommendations based on observed findings. We performed a two-stage systematic literature search using Pubmed, Web of Science, Cochrane Library, ALOIS, and Scopus (inception - July/September 2018, English and German). The first search purposed to identify motor assessments used in randomised controlled trials assessing effectiveness of physical activity in IWD and to display their frequency of use and effect sizes. The second search focused on psychometric properties considering influence of severity and aetiology of dementia and cueing on test-retest reliability. Two reviewers independently extracted and analysed findings of eligible studies in a narrative synthesis.

Results: Literature searches identified 46 randomised controlled trials and 21 psychometric property studies. While insufficient information was available for validity, we observed sufficient inter-rater and relative test-retest reliability but unacceptable absolute test-retest reliability for most assessments. Combining these findings with frequency of use and effect sizes, we recommend Functional Reach Test, Groningen Meander Walking Test (time), Berg

Balance Scale, Performance Oriented Mobility Assessment, Timed Up & Go Test, instrumented gait analysis (spatiotemporal parameters), Sit-to-Stand assessments (repetitions> 1), and 6-min walk test. It is important to consider that severity and aetiology of dementia and cueing influenced test-retest reliability of some assessments.

Conclusion: This review establishes an important foundation for future investigations. Sufficient relative reliability supports the conclusiveness of recommended assessments at group level, while unacceptable absolute reliability advices caution in assessing intra-individual changes. Moreover, influences on test-retest reliability suggest tailoring assessments and instructions to IWD and applying cueing only where it is inevitable. Considering heterogeneity of included studies and insufficient examination in various areas, these recommendations are not comprehensive. Further research, especially on validity and influences on test-retest reliability, as well as standardisation and development of tailored assessments for IWD is crucial. This systematic review was registered in PROSPERO (CRD42018105399).

Keywords

Cognitive impairment, frequency of use, physical performance measurements, reliability, validity

Author Contribution

My contribution to the systematic literature review was to support the systematic search and to discuss the results and help to structure the findings. I also assisted with the preparation of the manuscript and the peer-review process.

5.2.2 Research article 5: Reliability of physical performance tests with dementia-specific adaptations

Research Contribution

Continuing the consideration of psychometric properties, a reliability study was conducted as part of the structural evaluation. In this article, adaptations were made to commonly used physical performance tests in PwD. The contributions, similar to the previous research article, are therefore in the context of exercise science.

Reference

Barisch-Fritz, B., Krafft, J., Krell-Rösch, J., Woll, A. (2025). Dementia-specific adaptations to physical performance tests of balance, mobility, and lower limb strength and function: A

reliability study in people with dementia. BMC Geriatrics, 25 (1), 908. doi: 10.1186/s12877-025-06710-1.

Abstract

Introduction: Valid and reliable physical performance (PP) tests are crucial for accurately assessing the PP of people with dementia (PwD) and for evaluating the effects of interventions. However, existing PP tests for PwD often show insufficient reliability. This study aims to investigate the reliability of PP tests of balance, mobility and lower limb strength and function that were specifically adapted for PwD.

Methods: We conducted a reliability study with test-retest design and a one-week gap between tests among PwD living in nursing homes. The study used the Frailty and Injuries: Cooperative Studies of Intervention Techniques (FICSIT) for balance, the Timed-Up and Go Test (TUG) and its five phases for mobility, and the Sit-to-Stand test (STS) for lower limb strength and function. Adaptations were made to a) the instruction and administration, or b) the scoring of these tests. The tests were standardized in terms of cues used to administer and guide them. The absolute and relative test-retest reliability of the PP tests was assessed.

Results: We examined relative and absolute reliability values of PP tests in a sample of 26 PwD (mean age, 88 years; mean Mini Mental State Examination (MMSE) score, 14). No statistically significant differences were found between baseline and retest. Relative reliability values ranged from 0.258 to 0.505 for balance (FICSIT), 0.011 to 0.860 for mobility (TUG), and 0.506 to 0.678 for lower limb strength and function (STS). Absolute reliability values as indicated by the coefficient of variation (CV) ranged from 23.5 to 92.8.

Conclusions: Adaptations regarding test administration and/ or scoring did not improve reliability values as compared to the original test versions. TUG test phases showed the highest reliability values for the gait phases. Future adaptations should focus on reducing the cognitive component of tests. Technologies such as augmented reality and assistive technology could improve test reliability by providing more consistent and controlled test environment.

Keywords

Motor performance, motor tests, physical performance, psychometric properties

Author Contribution

My contribution to this research article was to design and support the conduction of the reliability study and the analysis. I wrote the article and was the corresponding author throughout the peer-review process.

5.2.3 Research article 6: Individualization approach to exercise interventions for people with dementia in nursing homes

Research Contribution

The challenge within the sample in terms of designing an exercise intervention is that the target group is extremely heterogeneous. This was found in the RCT and has been demonstrated in other studies. The heterogeneity relates to the cognitive and physical performance of PwD, which is relevant to the definition and delivery of the exercises. At the same time, there is a need for implementable solutions, especially because NHE should be able to instruct the exercise intervention. The research article provides an individualization approach based on a cluster analysis conducted on cognitive and physical performance data from 230 PwD. The contribution of this research article to the field of exercise science is high as it describes the methodology for identifying an individualization approach to exercise based on data from PwD.

Reference

Barisch-Fritz, B., Bezold. J, Scharpf, A., Trautwein, S., Krell-Roesch, J., Woll A. (2023). A new approach to individualize physical activity interventions for individuals with dementia: Cluster analysis based on physical and cognitive performance. Journal of Geriatric Physical Therapy, 47(3), 145-154. doi: 10.1519/JPT.0000000000000396.

Abstract

Background and purpose: Physical activity (PA) can have a beneficial effect on cognitive and physical performance in individuals with dementia (IWD), including those residing in nursing homes. However, PA interventions in nursing homes are usually delivered using a group setting, which may limit the effectiveness of the intervention due to the heterogenous nature of IWD. Therefore, the purpose of this study was to identify clusters based on cognitive and physical performance values, which could be used to improve individualization of PA interventions.

Methods: Based on the cognitive and physical performance variables of 230 IWD, a cluster analysis was conducted. Global cognition (Mini-Mental State Examination), mobility (6-Meter Walking Test), balance (Frailty and Injuries: Cooperative Studies of Intervention Techniques-subtest-4), and strength and function of lower extremities (30-Second Chair-Stand Test) were assessed, and values were used to perform a hierarchical cluster analysis with Ward's method. Differences in physical and cognitive performance as well as other secondary

outcomes (age, sex, body mass index, use of walking aids, diagnosis and etiology of dementia, number of medications, and Cumulative Illness Rating Scale) were tested using 1-factorial analyses of variance.

Results and discussion: Out of 230 data sets, 3-cluster solutions were identified with similar cluster sizes of 73 to 79. The silhouette coefficients for all calculated clusters ranged between 0.15 and 0.34. The cluster solutions were discussed in the context of cognitive and physical functions as well as training modalities and opportunities. The 4-cluster solution appears to be best suited for providing or developing an individualized PA intervention.

Conclusions: The identified clusters of the 4-cluster solution may be used in future research to improve individualization of dementia-specific PA interventions. By assigning IWD to these clusters, more homogenous groups with regard to cognitive and physical performance can be formed. This allows for more individualized PA interventions and may result in a higher effectiveness, particularly in nursing homes. Our findings are relevant for therapists and nursing staff who design or deliver PA interventions in nursing homes or similar settings.

Keywords

Alzheimer disease, cognitive and motor impacts, personalization, training groups

Author Contribution

My contribution to this research article was to design and conduct the exploratory analysis. I also initiated, prepared, and wrote this research article and was the corresponding author throughout the peer-review process.

5.2.4 Research article 7: Stakeholder analysis

Research Contribution

The design of the future exercise application was already considered at the structural evaluation level taking into account the end-users. For this purpose, an approach based on UX research methods was defined, in which a stakeholder analysis with subsequent definition of personas was carried out. The article contributes to the planning of an intervention using UX research approaches and the combination of sports science and UX research.

Reference

Barisch-Fritz, B., Barisch, M., Trautwein, S., Scharpf, A., Bezold, J., Woll, A. (2020). Designing a mobile app for treating individuals with dementia: Combining UX research with sports science. In: Lames, M., Danilov, A., Timme, E., Vassilevski, Y. (eds.) Full manuscript in Proceedings of the 12th International Symposium on Computer Science in Sport (IACSS 2019). IACSS 2019. Advances in Intelligent Systems and Computing, vol 1028. Springer, Cham. doi: 10.1007/978-3-030-35048-2_22.

Abstract

Dementia treatment requires new approaches to delay the progress of the disease. Based on research results to treat dementia a novel approach to combine results from sports science with user experience research (UX) has been taken to develop an application (app) to support hospitalized individuals with dementia by an individualized physical activity program. This paper describes the methodology to develop the app and the current state of the journey.

Keywords

UX research, dementia, physical activity, training in nursing homes

Author Contribution

My contribution to the article included the idea for the design and conduction of the survey. I prepared, and wrote this research article and was the corresponding author throughout the peer-review process.

5.2.5 Research article 8: Affinity for technology and technology interaction among nursing home employees

Research Contribution

In the area of structural evaluation, the nursing home setting was also examined in more detail. Due to the planned instruction of the exercise program by NHE, it was important to take a closer look at this target group and, as a first step, to investigate their affinity for technology and technical interaction. To this end, a Germany-wide online survey was conducted in nursing homes. The survey, and thus the research contribution, makes an important contribution to the planning and development of digital solutions as well as to the introduction and implementation of digital solutions in care facilities. The article contributes to user experience research, especially in the context of user-centered development.

Reference

Barisch-Fritz, B., Krafft, J., Rayling, S., Diener, J., Krell-Rösch, J., Möller, T., Wunsch, K., Sartorius, M., Riedel, N., Ferreira Maia, M.J., Weinberger, N., von Both, P., Asfour, T., Woll, A. (2023). Are nursing home employees ready for the technical evolution? German-wide survey on the status quo of affinity for technology and technology interaction. Digital Health. 21(9), 20552076231218812. doi: 10.1177/20552076231218812.

Abstract

Background: Technological devices can support nursing home employees; however, their perspective is not sufficiently studied. Our aims were thus to (a) examine affinity for technology and technology interaction and related sociodemographic confounders, as well as (b) detect possible requirements and boundary conditions relevant for the development and implementation of assistive technologies among nursing home employees.

Methods: We conducted an online survey between May and July of 2022 among 200 nursing home employees in Germany. The survey included two questionnaires, that is, Affinity for Technology Interaction (ATI) and Affinity for Technology—Electronic Devices (TA-EG; subscales TA-EG-Enthusiasm, TA-EG-Competence, TA-EG-Positive Consequences, and TA-EG-Negative Consequences), as well as sociodemographic variables, that is, age, gender, professional groups, education/graduation level. We carried out factorial variance and multiple regression analyses.

Results: There were differences between age groups in ATI (lower score with increasing age) and between gender, age, and professional group in TA-EG (lower score for females, participants with higher ages, and nursing home managers). Predictors of ATI were age and professional group, predictors of TA-EG, TA-EG-Enthusiasm, and TA-EG-Competence were gender, age, and professional group. Predictors of TA-EG-Positive Consequences were education and professional group.

Conclusions: We observed rather high affinity for technology and technology interaction values overall, and particularly for nursing home employees compared to managers. Significant predictors for technology affinity and interaction may have important implications, for example the perspectives of nursing home employees and managers should be considered separately in the technological design, development, and implementation process. Furthermore, an open dialogue between all stakeholders should be encouraged to increase the probability of actual technology use.

Keywords

Technology acceptance, digital transformation, care professional, assistive technology, older people

Author Contribution

I was involved in the design of the study and subsequently analysed the data for the research question. I also initiated and wrote the article and was the corresponding author throughout the peer-review process.

5.2.6 Research article 9: Application development in a sports science environment

Research Contribution

In Order to plan the development of the digital exercise intervention, it was also essential to consider the development of mobile applications from a sports science perspective at the structural evaluation level. To this end, a systematic review and a survey was carried out in an exemplary academic setting in order to define the development in terms of software engineering principles and roles in the development process, and thus optimally guide the development process. The research is essential for planning and implementing application development in an academic environment. In addition, it is an important contribution to the education of sports scientists, who are already finding their professional field in the context of digital health today and who can successfully enrich this field with their sports science expertise in the future.

Reference

Barisch-Fritz, B., Nigg, C., Barisch, M., Woll, A. (2022). App development in a sports science setting. Systematic review and lessons learned from an exemplary setting to generate recommendations for the app development process. Frontiers in Sports and active living, 4(4), 1012239. doi: 10.3389/fspor.2022.1012239.

Abstract

The digital health sector is rapidly growing. With only 4 % of publishers out of academic settings, it is under-represented in app development. The objective of this study is to assess the current state of app development with a systematic review and a survey within an exemplary academic setting along the following research questions: (Q1) Are software engineering

principles sufficiently known in the sports science app development context? (Q2) Is the role of sports scientists in the context of app development sufficiently understood? The systematic review was conducted by two independent reviewers within databases Pubmed, Scopus, Web of Science, and IEEE Xplore. The PICO schema was used to identify the search term. We subtracted information about five main topics: development process, functional requirements and features, security, technology, and dissemination. The survey was developed by a multidisciplinary team and focused on five main topics. Out of 701 matches, 21 were included in the review. The development process was only described in seven studies. Functional requirements and features were considered in 11 studies, security in 3, technology in 13, and dissemination in 12 with varying details. Twelve respondents [mean age 33(7) years, 58 % women] replied to the survey. The survey revealed limited knowledge in realization of security measures, underlying technology and source code management, and dissemination. Respondents were able to provide input on development processes as well as functional requirements and features. The involvement of domain experts is given in seven review studies and described in two more. In 50 % of survey respondents, the role in app development is defined as a research assistant. We conclude that there is a varying degree of software engineering knowledge in the sports science app development context (Q1). Furthermore, we found that the role of sports scientists within app development is not sufficiently defined (Q2). We present recommendations for improving the success probability and sustainability of app development and give orientation on the potential roles of sports scientists as domain experts. Future research should focus on the generalizability of these findings and the reporting of the app development process.

Keywords

Barriers of implementing apps, checklist, digital health, digitalization, mobile applications, software engineering.

Author Contribution

I was significantly involved in the design and implementation of the survey, conducted systematic review, and synthesised the results with my co-authors. I designed and wrote the article and was the corresponding author throughout the peer-review process.

5.3 Design and development management of the digital exercise intervention – Process evaluation of the iterative user-centered application development

Steps 3 and 4 of the IMF were to develop the digital exercise intervention in terms of incorporating relevant behavior change principles and designing the application with key content to enable the NHE to test cognitive and physical performance testing and subsequently traing PwD individually. In particular, the easy and targeted use of the InCoPE-App by NHE is crucial for the delivery of the exercise program and thus the generation of effects based on the individualized exercise program. Therefore, the aim of the development was to translate the dementia-specific multimodal exercise program with combined physical and cognitive exercises into a digital solution that can be used by NHE to instruct PwD. Furthermore, the aim was to define a user-centered, iterative approach by collecting and incorporating feedback at different levels. This was defined in the study protocol [research article 10 (Barisch-Fritz, Bezold, Scharpf et al., 2022b)]. End-user feedback to further improve the application was collected using a mixed methods approach [research article 11 (Krafft et al., 2023)].

The lack of evaluated applications increases the need to define the application development process. This study protocol provides an opportunity to evaluate both usability and effectiveness by using a mixed methods design. The main findings of the usability in-lab study of 14 NHE showed a good perceived usability of the InCoPE-App. The main usability problems were related to the navigation logic and the comprehensibility of the application content. In summary, the application can be used with little training, even by people aged ≥50 years, who may have low digital affinity and competence.

5.3.1 Research article 10: Definition of the iterative development process

Research Contribution

Based on the process evaluation, it was important to define the steps in which feedback will be used to improve the InCoPE-App in order to achieve the goal of an easy-to-use mobile application for NHE. For this reason, we defined a study protocol to evaluate the usability and effectiveness of the InCoPE-App using a mixed methods design.

Reference

Barisch-Fritz, B., Bezold, J., Scharpf, A., Trautwein, S., Krell-Rösch, J., Woll, A. (2022b). Usability and effectiveness of an individualized, tablet-Based, multidomain exercise program for people with dementia delivered by nursing assistants: Protocol for an evaluation of the InCoPE-App. JMIR Research Protocols, 11(9), e36247. doi: 10.2196/36247.

Abstract

Background: The COVID-19 pandemic has had drastic consequences on everyday life in nursing homes. Limited personnel resources and modified hygiene and safety measures (eg, no external exercise instructors, no group settings) have often led to interrupted physical exercise treatments. As a consequence, people with dementia benefiting from individualized exercise programs are affected by the pandemic's impact.

Objective: Our goal is to develop an easily applicable mobile application (Individualized Cognitive and Physical Exercise [InCoPE] app) allowing nursing assistants to test cognitive function and physical performance and subsequently train people with dementia through a multidomain, individualized exercise program.

Methods: We will evaluate the usability and effectiveness of the InCoPE-App by applying a mixed method design. Nursing assistants will use the InCoPE-App for 18 weeks to assess the cognitive function and physical performance of 44 people with dementia every 3 weeks and apply the individualized exercise program. We will record overall usability using questionnaires (eg, Post-Study System Usability and ISONORM 9241/10), log events, and interviews. Perceived hedonic and pragmatic quality will be assessed using the AttrakDiff questionnaire. Effectiveness will be evaluated by considering changes in quality of life as well as cognitive function and physical performance between before and after the program.

Results: Enrollment into the study will be completed in the first half of 2022. We expect an improvement in the quality of life of people with dementia accompanied by improvements in cognitive function and physical performance. The usability of the InCoPE-App is expected to be rated well by nursing assistants.

Conclusions: To date, there is no scientifically evaluated app available that enables nursing assistants without expertise in sports science to deliver an individualized exercise program among people with dementia. A highly usable and effective InCoPE-App allows nursing assistants to test cognitive function and physical performance of people with dementia and, based thereon, select and deliver an appropriate individualized exercise program based on the cognitive and physical status of an individual, even in times of a pandemic.

Keywords

Cognitive decline; cognitive function; cognitive performance; dementia; digital application; effectiveness; exercise; fitness; health app; institutionalization; institutionalized; long-term care; mHealth; mobile health; nursing home; physical activity; physical function; physical performance; sport; usability

Author Contribution

My contribution to this article was the design of the study to evaluate the usability and the effectiveness of the InCoPE-App. I also supervised and wrote the article and was the corresponding author throughout the peer-review process.

5.3.2 Research article 11: Mixed-method usability study

Research Contribution

The process evaluation includes the evaluation of the InCoPE-App in a laboratory setting and the assessment of feedback from former end-users using a mixed methods approach. The study was designed to encourage NHE to perform basic tasks of the InCoPE-App while applying a think aloud protocol and completing a usability questionnaire.

Reference

Krafft, J., **Barisch-Fritz, B.**, Krell-Rösch, J., Trautwein, S., Scharpf, A., Woll, A. (2023). A tablet-based app to support nursing home staff in delivering an individualized cognitive and physical exercise program for individuals with dementia: Mixed methods usability study. JMIR aging, 22(6), e46480. doi: 10.2196/46480.

Abstract

Background: The promotion of physical activity in individuals with dementia living in nursing homes is crucial for preserving physical and cognitive functions and the associated quality of life. Nevertheless, the implementation of physical activity programs in this setting is challenging, as the time and expertise of nursing home staff are limited. This situation was further exacerbated by the COVID-19 pandemic. Mobile health apps may be a sustainable approach to overcome these challenges in the long term. Therefore, the Individualized Cognitive and Physical Exercise-App (the InCoPE-App) was developed to support nursing home staff in delivering and implementing tailored cognitive and physical exercise training for individuals with dementia. Objective: This study aims to assess the usability of the InCoPE-App in terms

of user performance and user perception in a laboratory setting using a mixed methods approach.

Methods: Nursing home staff were encouraged to perform 5 basic tasks within the InCoPE-App. Their thoughts while using the app were captured by implementing a think aloud protocol. Then, participants completed the System Usability Scale questionnaire. The think aloud transcripts were qualitatively evaluated to unveil usability issues. All identified issues were rated in terms of their necessity to be fixed. Task completion (ie, success rate and time) and perceived usability were evaluated descriptively.

Results: A total of 14 nursing home employees (mean age 53.7, SD 10.6 years; n=13, 93 % women) participated in the study. The perceived usability of the InCoPE-App, as assessed by the System Usability Scale questionnaire, can be rated as “good.” The main usability issues concerned navigation logic and comprehensibility of app content.

Conclusions: The InCoPE-App is a user-friendly app that enables nursing home staff to deliver and implement cognitive and physical exercise training for individuals with dementia in nursing homes. The InCoPE-App can be used with little training, even by people aged ≥50 years, who may have low digital literacy. To achieve sustainable use and high user satisfaction of the InCoPE-App in the long term, it should be implemented and evaluated in a field study.

Keywords

Dementia, individualized physical exercise, tailored exercise, physical activity, older adults, app, mobile health, mHealth, usability, mobile phone

Author Contribution

My contribution to this study was to design the mixed methods approach of this usability study and to assist in the conduct and analysis of the study and the writing of the research article.

5.4 Results on the digital exercise intervention – Outcome evaluation based on usability and effectiveness of the InCoPE-App and possible extensions

The outcome evaluation is based on the study protocol described in the research article 10 and includes the assessment of the usability by end-users and the effectiveness on physical

and cognitive performance of PwD. The intervention was evaluated using a cohort study design with pre and post assessments in the two samples of NHE and PwD. Due to the COVID-19 pandemic, the study protocol could not be followed in terms of sample size. Therefore, only trends in effectiveness can be reported [research article 12 (Barisch-Fritz, Bezold, Scharpf et al., 2022a)]. The usability of the InCoPE-App was overall rated high by the NHE. In at least two assessed variables of global cognition, balance, mobility and lower limb strength and function, PwD maintained or improved after the 18-week intervention. The main improvements were found in balance, mobility, and lower limb strength and function. In general, adherence to the intervention was rather low due to COVID-19-related dropouts (Barisch-Fritz, Bezold, Scharpf et al., 2022a).

Further research is based on extensions of the exercise program with an implementation in VR [research article 13 (Prinz et al., 2024)]. Furthermore, given the challenges in measuring PwD, new options that do not rely on cognitive barriers need to be considered. This could be achieved by assessing physical performance based on assistive technologies such as exoskeletons. The feasibility of using immersive VR with PwD is positive. The study showed that there were no changes in physical, cognitive performance or emotional responses that would increase the risk of falling or other emotional responses during or after VR use. In fact, 72 % of the 33 PwD enrolled felt joy and fun, 100 % showed no emotions of anxiety, sadness, or anger, and 93 % were attentive during VR use (Prinz et al., 2024).

The benefits of assessing physical performance with wearable robotic devices are high, but there are several challenges for this use case. Wearable robotic devices, such as exoskeletons, have the potential to assess physical performance under real-life conditions, such as during physical activity and exercise, and thus could improve physical performance, especially in older adults with mobility impairments [research article 14 (Möller et al., 2025)].

5.4.1 Research article 12: Evaluation of usability and trends toward effectiveness of the InCoPE-App

Research Contribution

The outcome evaluation was conducted by using the InCoPE-App in nursing homes for 18 weeks. The pre-post design of the study was to assess the usability in the sample of NHE and the intervention effects in the sample of PwD before, during and after the use of the InCoPE-App. Due to the small sample of pandemic-related challenges and dropouts, no conclusive statistics could be used to consider the effects.

Reference

Barisch-Fritz, B., Bezold, J., Scharpf, A., Trautwein, S., Krell-Rösch, J., Woll, A. (2022a). ICT-Based individualized training of institutionalized individuals with dementia. Evaluation of usability and trends towards effectiveness of the InCoPE-App. Frontiers in Physiology, 8(13), 921105. doi: 10.3389/fphys.2022.921105.

Abstract

Physical activity interventions can alleviate the course of disease for individuals with dementia (IWD) who have been extraordinarily affected by the COVID-19 pandemic. Information and Communication Technology (ICT) provides new opportunities not only to mitigate negative effects of the pandemic but also to sustainably improve everyday life of IWD in nursing homes. The aim of the present study was to evaluate the ICT-based InCoPE-App, which was used to assess physical and cognitive performance and deliver individualized exercise for IWD, with regard to 1) user experience of nursing assistants, and 2) trends toward the effectiveness of the intervention on physical and cognitive performance of IWD. An 18-week individualized multidomain intervention (2 × 60 min/session) was delivered to an intervention group (IG; n = 10, mean age 88.4 ± 5.6, 70 % female) by nursing assistants (n = 10, mean age 56.1 ± 10.4, 90 % female) using the InCoPE-App. A control group (CG; n = 3, mean age 87.3 ± 3.5, 100 % female) received conventional treatment. User experience was assessed among nursing assistants by different questionnaires, i.e., PSSUQ and ISONORM 9241/110-S for usability, and AttrakDiff2 for pragmatic (PQ), hedonic quality-identity and stimulation (HQI and HQS), and attractiveness (ATT). Trends toward the effectiveness of the intervention were assessed using MMSE (global cognitive function), FICSIT-4 (balance), 6MWT and TUG (mobility), and m30CST (function of lower limbs). Usability of the InCoPE-App was rated as high by nursing assistants (mean ± SD; overall PSSUQ 2.11 ± 0.75; overall ISONORM 9241/110-S 1.90 ± 0.88; ATT 1.86 ± 1.01; PQ 1.79 ± 1.03; HQI 1.8 ± 0.79; and HQS 1.37 ± 0.69). Dropout was high in the total sample (36.7 %). Trends toward the effectiveness were observed within IG in nine IWD who showed positive or neutral trends in at least two physical performance outcomes. Seven participants had positive or neutral trends in the FICSIT-4, seven participants in m30CST, and four and seven participants in 6MWT and TUG, respectively. In conclusion, the InCoPE-App has good nursing assistant-rated usability, whereas training effects and intervention adherence were rather low most likely due to COVID-19 restrictions. Single-subject research revealed more positive than negative trends in IG of IWD. Further research is needed to evaluate feasibility, suitability, and effectiveness of the InCoPE-App.

Keywords

Alzheimer's disease, digitalization and e-health, feasibility, mobile application, physical activity

Author Contribution

My contribution to the study was substantial, ranging from design and implementation to data preparation and analysis. I wrote the article and was the corresponding author throughout the peer-review process.

5.4.2 Research article 13: Feasibility of the use of immersive virtual reality in people with dementia

Research Contribution

VR with its highly stimulating nature, could be considered as an extension of the exercise program for PwD. Immersive VR could also be used to complement promising non-pharmacological treatments, such as music therapy or biographical work, and combine them with PA promotion. To this end, we started by investigating the feasibility of using immersive VR with PwD. We looked at changes in physical and cognitive performance as well as emotional responses to the use of immersive VR.

Reference

Prinz, A., Buerger, D., Krafft, J., Bergmann, M., Woll, A., Witte, K.*, **Barisch-Fritz, B.*** (2024). Use of immersive virtual reality in nursing homes for people with dementia: Feasibility study to assess cognitive, motor, and emotional responses. JMIR XR Spatial Comput 1(1), e54724. doi: 10.2196/54724. *equal contribution

Abstract

Background: Physical activity interventions for people with dementia have shown promising effects in improving cognition and physical function or slowing disease-related decline. Immersive virtual reality (iVR), using head-mounted displays, facilitates realistic experiences by blurring the boundaries between VR and the real world. The use of iVR for people with dementia offers the potential to increase active time and improve dementia therapy and care through exercise interventions. However, the feasibility of using VR use in people with dementia, considering changes in motor, cognitive, psychological, and physiological parameters, remains insufficiently investigated.

Objective: This study aims to investigate the feasibility of using iVR in people with dementia or mild cognitive impairment in nursing homes. Specifically, we examined changes in motor performance (balance and mobility), cognitive performance (global cognition and executive functions), emotional responses, and fear of falling using iVR.

Methods: Utilizing a pre-post design, this study recruited 35 participants with mild-to-moderate dementia, assessed by the Mini-Mental State Examination (MMSE). Participants underwent a single session involving iVR exposure, with pre- and postexposure assessments and a feedback form, to exclude negative effects on cognitive and motor functions, mood, anxiety levels, and balance performance. The use of iVR involved 4 scenes, with a total length of 8 minutes. These scenes depicted a park with short and rather passive impressions presented as a 360° video in a head-mounted display. Before and after using the iVR, cognitive parameters were assessed using the Trail-Making Test A (TMT-A), motor parameters were assessed using the FICSIT-4 (Frailty and Injuries: Cooperative Studies of Intervention Techniques-4) and Timed-Up-and-Go (TUG) tests, and psychological parameters were assessed using the Dementia Mood Picture Test, State-Trait Anxiety Inventory, and Short Falls Efficacy Scale-International (Short FES-I). The Emotion Rating Scale and the duration of use were recorded during use, and a feedback questionnaire was completed afterward in addition to the posttests. Paired t tests and Wilcoxon tests were used to examine pre-post differences.

Results: Of the 35 initial participants, 33 completed the study, which corresponds to a dropout rate of 6 %. All 33 participants, who had a mean of 83.71 (SD 5.01) years, had dementia. They showed no statistically significant difference in cognitive and motor performance before and after iVR use. Thus, no negative effects on cognitive and motor functions, mood, anxiety levels, and balance performance were observed. The emotion rating scale also showed that 72 % (n=24) felt joy and fun during iVR use, 100 % (n=33) showed no emotions such as fear, sadness, or anger, and 93 % (n=31) were attentive during iVR use.

Conclusions: The feasibility of using iVR for people with dementia can be rated positively. There were no changes in motor, cognitive, or emotional parameters that would increase the risk of falls or other negative emotional reactions during or after iVR use. Further studies are needed to investigate prolonged use in a more stimulating computer-generated environment and possible physical and cognitive tasks for people with dementia in nursing homes.

Keywords

Persons with dementia, Virtual Reality, HMD, physical performance, Alzheimer’s disease

Author Contribution

The study was conducted in collaboration with the University of Magdeburg. I contributed to the design and implementation of the feasibility study, supervised the study and partly wrote the article. I also submitted the article and acted as corresponding author. The contribution of the last two authors is equal.

5.4.3 Research article 14: Assessing physical performance with lower limb exoskeletons

Research Contribution

In the future, it may be possible to use assistive technologies to assess physical performance in real-life settings and conditions. This would help in a number of ways, as there are several issues with clinical testing in older adults. In particular, the problem of instructional delay, which is a specific problem in PwD, could be addressed by assistive technologies such as wearable robots or exoskeletons. This research article aims to bring together different perspectives on the opportunities, benefits, and challenges of using exoskeletons to assess physical performance in older adults.

Reference

Möller, T., Beyerlein, M., Herzog, M., **Barisch-Fritz, B.**, Marquardt, C., Dezman, M., Asfour, T., Woll, A., Stein, T., Krell-Rösch, J. (2025). Human motor performance assessment with lower limb exoskeletons as a potential strategy to support healthy aging-a perspective article. Prog Biomed Eng (Bristol). 2025 Jan 8;7(1). doi: 10.1088/2516-1091/ada333.

Abstract

With increasing age, motor performance declines. This decline is associated with less favorable health outcomes such as impaired activities of daily living, reduced quality of life, or increased mortality. Through regular assessment of motor performance, changes over time can be monitored, and targeted therapeutic programs and interventions may be informed. This can ensure better individualization of any intervention approach (e.g., by considering the current motor performance status of a person) and thus potentially increase its effectiveness with regard to maintaining current performance status or delaying further decline. However, in older adults, motor performance assessment is time consuming and requires experienced examiners and specific equipment, amongst others. This is particularly not feasible in care facility/ nursing home settings. Wearable robotic devices, such as exoskeletons, have the

potential of being used to assess motor performance and provide assistance during physical activities and exercise training for older adults or individuals with mobility impairments, thereby potentially enhancing motor performance. In this manuscript, we aim to 1) provide a brief overview of age-related changes of motor performance, 2) summarize established clinical and laboratory test procedures for the assessment of motor performance, 3) discuss the possibilities of translating established test procedures into exoskeleton-based procedures, and 4) highlight the feasibility, technological requirements and prerequisites for the assessment of human motor performance using lower limb exoskeletons.

Keywords

Wearable robotics, ambulatory, assessment, older adults, gait, posture, strength, proprioception

Author Contribution

My contribution to this work was to develop the idea of combining clinical and biomechanical testing using assistive technology. I also assisted with the writing of the article and the peer-review process.

6 Discussion

The discussion is structured into four chapters. Chapter 6.1 discusses the key findings of the 14 research articles from the two research areas of the effects of PA and exercise on PwD and the planning and design of the digital exercise intervention (see Chapter 5). Chapter 6.2 discusses the application of the six steps of the IMF with a focus on further improvements and lessons learned in relation to the design and planning of the digital exercise intervention for PwD in nursing homes. Chapter 6.3 presents an approach to extending the IMF so that it can be used as a generic approach to planning and designing theory- and evidence-based, user-centered digital exercise interventions. Chapter 6.4 concludes with a consideration of the limitations of the application of the IMF and the results obtained in this habilitation thesis.

6.1 Discussion of the obtained results

This habilitation thesis has generated a number of results that can be allocated to planning, structure, process, and outcome evaluation. These results relate to the research question of theory- and evidence-based planning and design of a digital exercise intervention for PwD (see Chapter 3.2), applicable to NHE, that counteracts the age- and disease-related cognitive and physical decline. Thus, the results fall under the two research areas of the effects of PA and exercise in PwD (mainly planning and outcome evaluation) and the planning and design of a digital exercise intervention (mainly structure and process evaluation).

At the level of the planning evaluation, the effects of a real-world approach based on a group-based exercise intervention specifically designed for PwD were investigated (Barisch-Fritz, Shah et al., 2025; Barisch-Fritz, Trautwein et al., 2022; Bezold et al., 2021). No statistically significant effects were found for physical and cognitive performance or ADL (Barisch-Fritz, Shah et al., 2025; Barisch-Fritz, Trautwein et al., 2022; Bezold et al., 2021). However, analysis using an ML approach showed that participation in the exercise intervention contributed to the better prediction of cognitive decline in PwD (Barisch-Fritz, Shah et al., 2025). Responder analyses also showed that 28 to 40 % of PwD who participated in the exercise intervention showed benefits in balance, mobility, and lower limb strength and function (Barisch-Fritz, Trautwein et al., 2022). In terms of the cognitive performance, 23 to 49 % showed no decline within 16 weeks, i.e., in attention and executive function, language, visuospatial skills, and memory (Barisch-Fritz, Shah et al., 2025). Based on a disease duration of 3 to 4 years for mild dementia and 1 to 2 years for moderate to severe dementia (Brück et al., 2021), with an often very progressive course, a positive effect on cognitive and physical performance can be

considered very successful. This assessment is supported by the observation that the length of stay in nursing homes is becoming shorter and that half of the residents dies within the first year of admission (Rothgang & Müller, 2023).

The effects of other studies, summarized in Chapter 2.2.3, showed mixed results for both physical and cognitive outcomes. The most promising approach was the multimodal exercise intervention approach. The reported effectiveness of multimodal interventions for PwD on cognitive function ranged from medium (0.29 Cohen's d) to large (2.02 Cohen's d) effect sizes (Sharew, 2022). A possible explanation for the lack of statistically significant effects within our RCT could be the low degree of individualization within the group-setting. This is supported by the finding that people with lower baseline physical performance benefited most from the multimodal exercise intervention (Barisch-Fritz, Trautwein et al., 2022). Therefore, an individualization approach was developed and training clusters were identified (Barisch-Fritz, Bezold et al., 2023). This individualization approach was integrated into the InCoPE-App. The training clusters of PwD were very different in terms of their cognitive and physical performance (mobility, balance and lower limb strength and functionality), which had not been previously investigated. The exercise program was adapted accordingly. The outcome evaluation showed positive trends in the effects of the digital exercise intervention with the InCoPE-App in the areas of global cognition as well as mobility, balance, and lower limb strength and function (Barisch-Fritz, Bezold, Scharpf et al., 2022a). In general, the exercise content was defined on the basis of the known effects and findings of exercise science in the field of aging research (see Chapter 2.2). With regard to the mechanisms of action on cognitive function (see Chapter 2.2.2), which are mainly found in endurance training, it can be speculated that the exercise intervention contains too few endurance elements or training volumes. This is a consequence of the vulnerability of the sample, increased by the group setting, in which endurance training is always associated with an increased risk of falls.

The effects on physical performance are important in a number of ways. First, physical decline has been found to accompany cognitive decline, or physical decline often precedes cognitive impairment. In particular, gait variability can predict the onset of MCI (Fuentes-Abolafio et al., 2020). The diagnosis of cognitive decline based on physical performance has therefore already been evaluated (Seifallahi et al., 2022). If the link is brain-based, an improvement in physical performance could be associated with an improvement in the symptoms or even causes of the disease in the brain. This is not yet proven, but studies using biomarkers are promising. Second, maintaining mobility is a highly relevant goal in care, as it directly determines the need for care and the amount of care required (Wohlrab et al., 2022). This is particularly important in the context of the nursing shortage and the wider care crisis, but also for the individual’s quality of life (Webber et al., 2010). The combination of physical and cognitive exercises in a social context makes a valuable contribution to the treatment of

PwD and to maintaining their quality of life, particularly in the context of limited provision and offers within nursing homes.

Considering of the reliability of the assessments is relevant for the evaluation of the effects of the exercise intervention, but also for the control of the individualization and therefore the suitability for the digital application and the training control within the digital application. Thus, it can be seen as an interface and the consideration of the psychometric properties of the assessments for the recording of physical performance is highly relevant (Trautwein, Maurus et al., 2019). In general, it has been shown that the assessments, which were mainly derived from geriatrics and not specifically developed for PwD have deficits, especially in terms of absolute reliability (Trautwein, Maurus et al., 2019). Test-retest reliability was sufficient for several assessments, i.e., the Groningen Meander Walking Test, the Timed Up & Go Test, the Sit-to-Stand Test, and the 6-minute walk test. The conclusion was that it is important to adapt these assessments to the severity of dementia and to standardize the cueing during the assessment (Trautwein, Maurus et al., 2019). The derived adaptations, which we applied in a reliability study, still did not show sufficient improvements in reliability (Barisch-Fritz, Krafft et al., 2025). Therefore, new approaches are needed that take greater advantage of digitalization. For example, augmented reality (AR) can be used to assess physical performance in ADL while reducing the cognitive component, e.g., through visualization and gamification. This is particularly relevant in the context of people with cognitive impairments, as current assessment of physical performance is often overshadowed by cognitive components, as tasks are often only verbally instructed or demonstrated.

Further results at the level of structure and process evaluation can be attributed to the planning and design of the digital exercise intervention for PwD in nursing homes. Here the findings are much broader and relate to the target group of people who will ultimately use the application, i.e., the NHE. An online survey found a general affinity for technology among NHE, but less at management level (Barisch-Fritz, Krafft et al., 2023). This is crucial for implementation as management is the decision maker. Knowledge transfer approaches need to be integrated at management level. In addition, information on possible reductions in the amount of care required, and thus in the cost of care, is of great importance in evaluating the outcomes.

The application development process was essentially defined by combining of sports science knowledge with methods from UX research and software development (Barisch-Fritz et al., 2020). UX methods were used to contribute to user-centered development. User-friendly design is central to the use of the application and therefore has a direct impact on the effectiveness of the intervention (Huang & Benyoucef, 2023; Priyadarshini, 2024). The lack of user involvement in the development process has been a major criticism of digital health

interventions in the past, along with a lack of theoretical underpinning, fundamental considerations of human-technology interface design, health behavior, and communication theory (Marcolino et al., 2018). This criticism has been used as an explanation for the low adherence and thus low effectiveness of digital interventions that is often observed in reality (Kernebeck et al., 2021).

The importance of integrating theoretical foundations and involving users in the development of digital interventions has been recognized, at least at a scientific level. Usability is also included in the evaluation plan for approval as a digital health application (DiGA). Furthermore, the overview in Chapter 2.3.3 shows that, in the context of the application of the IMF, 8 studies indicated that they had already integrated usability approaches in the needs assessment (Step 1 of the IMF) and in the program production (Step 4 of the IMF). Fifteen reported that they had made specific adjustments to the standard application of the IMF. The planning of the user participation within an iterative development process was also important in the development of the InCoPE-App, which is why the study protocol for the evaluation of usability and effectiveness was published (Barisch-Fritz, Bezold, Scharpf et al., 2022b). This is an important contribution as there have been very different approaches to evaluating usability. As part of the process evaluation, results on the usability of the application were repeatedly generated and interim results were also analyzed using a mixed methods approach (Krafft et al., 2023). The resulting findings of 14 NHE was a good overall usability but deficits in navigation logic and comprehensibility of app content. These usability issues were addressed in the next development iteration.

The actual development of the InCoPE-App was carried out by an external company, as was the case with other applications, as the research showed (Table 2, Chapter 2.3.3). The consideration of the development environment plays an essential role in the implementation. This was investigated in the present work as part of a systematic research and lessons learned analysis and can be summarized as follows: sports scientists play an essential role in the development process of digital exercise interventions (Barisch-Fritz, Nigg et al., 2023). In order to fulfil this role, basic knowledge of software engineering, but also of UX research, is necessary to be able to perform these tasks successfully. This has direct consequences for the education of sports scientists and thus for the design of the courses. The outcome evaluation showed a very positive assessment of usability (Barisch-Fritz, Bezold, Scharpf et al., 2022a), which may indicate a successful integration of end-users into the development process and thus the effect of the intervention is not impaired by operational difficulties or other usability limitations.

This high rating of the usability of the InCoPE-App is also an important contributor to potential adherence to the exercise intervention. We observed high adherence during COVID-19

when the wards had no current coronary events (Barisch-Fritz, Bezold, Scharpf et al., 2022a). This suggests that the InCoPE-App is both feasible and sustainable. With increased use of the app, knowledge transfer will take place in the PA promotion in nursing homes. Currently, there are few training opportunities in this area and it is clear that the long-standing concept of 'active care' has not yet been sufficiently integrated into everyday care (Ververda & Hauge, 2019b, 2019a). This is certainly due to challenging working conditions and time resources, but also to a lack of skills and interdisciplinary approaches. This is where the digital application has clear advantages. What would otherwise only be possible through longer (and actually not sufficiently available) training courses, can be achieved through the digital application by learning by doing. PA can be promoted without uncertainty on the part of the NHE and without increasing the risk due to ignorance. Due to a lack of human and time resources, it cannot be assumed that all NHE will take advantage of digital training and thus acquire knowledge to promote PA. Therefore, a digital application offers great opportunities. It creates knowledge transfer and provides access to scientifically evaluated services for nursing home residents in general and for PwD in particular.

Digital services also offer nursing homes the possibility of autonomy, i.e., the ability to provide PA services offers without external providers. This became increasingly necessary during the COVID-19 pandemic. During this time, almost all nursing homes reduced or stopped all services, including PA therapy (Giri et al., 2021). With the InCoPE-App, we were able to provide PA despite many challenges and even complete the study, albeit on a much smaller scale than planned. This role of technology was also seen in a study promoting social participation in PwD (Hoel et al., 2022).

6.2 Discussion of the Intervention Mapping Framework application and suggestions for adaptaions to digital intervention planning

The success of a digital intervention depends on several factors (although success is difficult to define and measure). A digital application focusing on lifestyle factors such as PA in the context of health and healthcare needs to be carefully developed to ensure its impact on users and its effectiveness. Lack of adherence and the resulting limited overall effectiveness of digital interventions are often related to unmet user needs, but also to deficits in the theoretical basis or the lack of fundamental considerations in the design of the human-technology interface (Kernebeck et al., 2021; Marcolino et al., 2018; Schnall et al., 2016). This critique of existing digital interventions was addressed in this habilitation thesis by applying the IMF. This ensured that the integration of multiple theories as well as the needs of the target group were adequately addressed. All six steps of the IMF were considered in the design and

evaluation of the InCoPE-App. This is described in detail in Chapter 4.2. Due to the iterative and cumulative nature of the IMF, these steps are not presented in the form of a deficit analysis, but rather in the form of continuous improvement through further iteration in order to achieve greater effectiveness.

Step 1 (see Chapter 4.2.1) defines the needs, objectives, and outcomes of the digital exercise intervention by developing the logic model of the problem. This was based primarily on existing literature and on the experience of the research team with the real-life approach in the study "Bewegung gegen Demenz". In a further iteration, targeted focus group discussions could be used to improve the content of the exercise intervention. It is known that the uptake and maintenance of exercise and sports depends on whether the exercise matches one's own motives (Ley, 2020; Molanorouzi et al., 2015). However, this knowledge is not sufficiently integrated into treatment and care settings. The potential is obvious, but implementation in these settings is more challenging. However, different motives addressed by, for example, ball games or dance, could be integrated and tailored to individuals. Adaptation in this way could therefore increase adherence to the intervention, thus adding a further level of personalization. In addition, focus group interviews with NHE could be used to improve the content by identifying and incorporating specific requests for training to promote PA and other supporting elements such as documentation. The InCoPE-App can help to overcome barriers to PA implementation, which are often related to a lack of interdisciplinary collaboration. This barrier was identified in a focus group discussion on the facilitators and barriers to PA in nursing homes (Trollebø et al., 2024). As Table 2.2 in Chapter 2.3.3 shows, many other research groups have used Step 1 of the IMF to plan technical features or general technical implementations in a user-centered way. Here, a further iteration could certainly help to better integrate the InCoPE-App into the everyday life of NHE.

In Step 2 (see Chapter 4.2.2), a next iteration could include a more in-depth and possibly expanded consideration of possible determinants, also with a focus on the organizational conditions of nursing homes. Based on the digital development in which the current consideration of technology affinity took place, further aspects of later technology acceptance or adoption should be considered. Additional determinants are relevant and need to be considered in the context of the relevant models and theories (Mkhonto & Zuva, 2024). A study using IMF in the context of designing of a digital intervention concluded that a better understanding of acceptability in the respective context could increase the adherence to the behavior and thus intervention effectiveness (Berry et al., 2023). Other UX methods can be applied in this context, such as persona description or stakeholder analysis, which may help to identify or address other determinants in the respective context. In addition, other outcomes that directly assess the need and the extend of care that optimally assess a change in care

need, should be included. These factors are relevant to the challenges of an ageing society and healthcare.

Behavioral change techniques and their translation into technical features were not integrated in depth in Step 3 (see Chapter 4.2.3). Specific behavioral change techniques are crucial for the success of digital interventions focusing on PA (Fiedler et al., 2020). The rather low implementation of this knowledge is due to the fact that the use of the InCoPE-App depends more on organizational structures than on personal factors of behavior adoption and maintenance. In addition, the lifestyle change is controlled by the end-user, it is not directed at PwD. However, if we consider that the digital application can also serve to increase knowledge about PA, this can also be seen in a different way. Namely, that the knowledge can also be used to initiate behavior changes in the NHE towards a more active and thus possibly healthier lifestyle. This is a relevant goal in the context of care, as NHE themselves are particularly vulnerable to physical and psychological stress and illness, for which PA can also have a preventive effect (Herz et al., 2024; Lambert et al., 2016). In a further iteration, additional elements from behavioral change techniques tailored to NHE could be integrated.

Step 4 (see Chapter 4.2.4) aims to develop the digital platform and content. Considerations of implementation and evaluation are also very important here. The specific software development of the digital intervention is often not described in detail, while our approach can serve as an example. UX methods for the design of the user interface, such as wireframes or visual identity, as well as the combination of the user journey map with the personas, help to adequately represent the user perspective (Bordegoni et al., 2023). In addition, mixed methods approaches are promising for identifying existing gaps, especially in nursing and health sciences, and can provide a better understanding of the links between theory and empirical findings (Östlund et al., 2020), also in the context of digital applications and user-centered adaptations.

The development of a digital intervention requires certain insights into its implementation, including a clear definition of the end-users and the program users who are important for the adoption, implementation and maintenance of the intervention. Furthermore, the external conditions of technology acceptance, technical equipment, etc. are of particular importance for the development. These basic considerations have been made within Step 5 (see Chapter 4.2.5), as it is immediately necessary in the context of application development. The actual implementation and distribution/dissemination would require a further refined implementation plan, which could be addressed in a further iteration. Dissemination is very important and often not adequately addressed, especially in academic projects. There are some challenges here, such as the lack of options for long-term maintenance and support of a digital

application. Nevertheless, it is important to plan from the beginning how the digital application will be implemented and distributed, and how it will be maintained.

The evaluation plan was well thought out in step 6 (see Chapter 4.2.6) and referred to several evaluation levels. The results are discussed in Chapter 6.1. Both the process and outcome evaluation included results related to the intervention as well as the acceptance of the digital application. This is necessary in order to achieve the greatest possible effect and also to identify possible shortcomings, especially at the level of acceptance, which can be adjusted in further development steps.

In summary, the use of the IMF has shown great value in achieving the objectives of a theory- and evidence-based, user-centered digital intervention. However, the use of this framework needs further legitimization as there are other frameworks in the context of digital health. One framework is IDEAS (Integrate, Design, Assess, and Share) (Mummah et al., 2016). The IDEAS framework has been described as combining existing knowledge by integrating behavioral theory, design thinking, evaluation, and dissemination (Mummah et al., 2016). However, the IDEAS framework has been mainly used in early childhood development programs and has not been extended to other settings and target groups.

From the experience of using the IMF for the design and planning of the InCoPE-App, the tasks (see Table 7) formulated by the IMF (Bartholomew Eldredge et al., 2016) did not sufficiently cover the objective of planning and designing a digital exercise intervention. Several examples in the literature, as systematically evaluated in Table 2.2 of Chapter 2.3.3, made adaptations to satisfy the digital nature of the intervention. However, there is no pooled information available that can be used as a guideline and possible quality requirement for digital exercise interventions in the healthcare context. Therefore, I propose the explicit extensions of the IMF within each of the 6 steps as shown in Table 7 as recommended 'digital adjustments'. The processing of the tasks and work steps recommended within the IMF is considered necessary, and the extensions and adjustments also include the fact that omitting a step can significantly affect the effectiveness of the intervention (Bartholomew Eldredge et al., 2016). In addition, the extension is also not linear to understand but iterative and cumulative. The examples from the studies in Table 2.2 serve as guiding implementation examples but can be adapted to the respective context and extended with other methods, theories or frameworks. The adaptations I propose are intended as a basis for action in the theory- and evidence-based design, planning and evaluation of user-centered digital exercise interventions.

Table 6.1: Digital adjustments to the Intervention Mapping Framework

STEP	TASKS	DIGITAL ADJUSTMENTS	LITERATURE EXAMPLES
Step 1 Logic Model of the Problem	• Establish and work with a planning group • Conduct a needs assessment to create a logic model of the problem • Describe the context for the intervention including the population, setting, and community • State program goals	• Integrate software developer • Define the needs in the context of digital support, preconditions, and preferences of the target group • Describe the digital environment and its technical conditions (i.e., WiFi availability, technical equipment)	• Interviews with end-users, relatives, and nursing and healthcare staff (Blacket et al., 2024; Busse et al., 2021; Golsteijn et al., 2017) • Multidisciplinary committees including app developers (Svendsen et al., 2022; Zuidema et al., 2015) • Needs analysis from user perspective (Svendsen et al., 2022) • Needs analysis regarding presentation modes and functional features of the application (Y. Chen et al., 2019) • Active participation of patients (Zuidema et al., 2015) • Focus group interviews (Sanders et al., 2023; Sassen et al., 2012) • Survey of the public and end-users on the concept and features of the planned application and on experiences/usage for tracking physical activity (Sanders et al., 2023)
Step 2 Program Outcomes and Objectives	• State expected outcomes for behavior and environment • Specify performance objectives for behavioral and environmental outcomes • Select determinants for behavioral and environmental outcomes • Construct matrices of change objectives • Create a logic model of change	• Determine the conditions of usability • Specify the conditions of technology acceptance in its specific context and, if possible, choose an underlying technology acceptance/adoption model or theory • Define and consider your development environment	• Prioritization of needs according to MoSCoW to determine features and functions (Lobo et al., 2023) • Process evaluation of the previous study to assess, among other things, possible solutions to unmet needs through the implementation of eHealth (Den Bakker et al., 2019)

Step 3 Program Design	• Generate program themes, components, scope, and sequence • Choose theory- and evidence-based change methods • Select or design practical applications to deliver change methods	• Prioritization of features • Conversion of BCT to digital BIT	• Prioritization of needs through MoSCoW (Sanders et al., 2023) • Implementation of theoretical and practical strategies in coordination with stakeholders (Lobo et al., 2023) • Questionnaires for focus groups (Boekhout et al., 2017) • Übertragung der BCT in digitale z.B. BIT (Direito et al., 2018)
Step 4 Program Production	• Refine program structure and organization • Prepare plans for program materials • Draft messages, material, and protocols • Pretest, refine, and produce materials	• Plan an interactive development process and build the development team based on current agile approaches • Use guidelines (i.e., iOS and Android) for feature design, etc. • Produce digital content and delivery format • Pretests with end-users	• **Development**: by ICT companies (Sanders et al., 2023) or in collaboration (Zuidema et al., 2015), based on iOS developer guidelines (Potzel et al., 2021), development of digital prototypes (Berry et al., 2023) • **Content creation**: creation of content through brainstorming and workshops, testing and refining, creation of personas, involvement of stakeholders and target groups (Svendsen et al., 2022), identification of functionalities (Lobo et al., 2023), implementation of BCTs into "user-centered" app functions using IMF and BIT (Direito et al., 2018) • **Process evaluation** (partially listed under steps 6): to simplify the baseline intervention and feasibility check (Golsteijn et al., 2017), to gain insights on functionalities, patient needs, program use and usability (Engelen et al., 2020; Hallsworth et al., 2021)
Step 5 Program Implementation Plan	• Identify potential program users (adopters, implementers, and maintainers) • State outcomes and performance objectives for program use • Construct matrices of change objectives for program use • Design implementation interventions	• Plan implementation including considerations based on trainings formats or addressing specific groups (beside end-users, like managers that decide about implementation) • Examine legal and technical requirements for the use of the digital interventions • Identify implementation challenges • Plan dissemination	• Normalization Process Theory to identify determinants of adoption and implementation (Svendsen et al., 2022) • Focus group discussions to disseminate and increase awareness (Puijk-Hekman et al., 2017)

Step 6 Evaluation Plan	• Write effect and process evaluation questions • Develop indicators and measures for assessment • Specify the evaluation design • Complete the evaluation plan	• Plan the process evaluation (i.e., When are interim results needed?) • Check usability according to the chosen acceptance model	• **Process evaluation** • **Pre-tests**: on feasibility, usability and acceptability, especially mixed methods approach with end-users (Berry et al., 2023; Hallsworth et al., 2021; Plaete et al., 2015; Potzel et al., 2021; Puijk-Hekman et al., 2017; Svendsen et al., 2022; Zuidema et al., 2015) • **Focus group discussions**: on user involvement (Palacz-Poborczyk et al., 2022), to apply the software development life cycle (Jaffar et al., 2022), to identify potential problems in terms of acceptance and usability (Hallsworth et al., 2021)

Building on this extension and with a view to the growing market for digital exercise interventions, basic knowledge can be defined for successful participation in such a development process. The growing market offers a good opportunity for sport scientists to actively shape it. When considering the app development environment, essential roles for sports scientists in the development of exercise applications have already been defined, namely that of the domain expert (i.e., product owner or subject matter expert in agile working methods) (Barisch-Fritz, Nigg et al., 2023). A basic understanding of software engineering and agile working should be available, and UX methods and techniques for behavior change should be known and, even better, applicable. In order to fulfil the role of the domain expert, movement and exercise science must remain at the core, accompanied by a good understanding of health and the social context, as well as good methodological and statistical knowledge. This is the only way to shape the sports science perspective on digitalization, which includes both the digital delivery of PA and the embedding of PA in the above-mentioned areas. This will strengthen the position of sport science in the field of digital health and make it easier for future sport scientists to enter the digital development landscape.

6.3 Limitations of this habilitation thesis

This habilitation thesis provides a comprehensive and holistic overview of the development of a theory and evidence-based, user-centered exercise intervention for PwD in nursing homes. The strengths in the extension and application of the IMF are worth to be highlighting. In particular, the extension gives the approach the value of a generic approach for the development of digital exercise interventions. In addition, important insights were gained into the nursing home setting and the applicability of digital exercise interventions in everyday care, even under the limitations of COVID-19.

However, as with any work, there are limitations. First and foremost, the sample size of the evaluation of the InCoPE-App for the outcome evaluation was too small (see Chapter 5.4.1). Thus, the final evaluation of the effects of the digital intervention on the physical and cognitive performance of PwD is still pending. This is due to the fact that the intervention took place during the COVID-19 pandemic. As a result, the required and previously calculated sample size could not be reached. It is almost surprising that the study could be continued at this stage, even ithough very strict restrictions were imposed in the German nursing homes. In conclusion, the preliminary results show the potential of this digital intervention, but it is obvious that a RCT is needed to demonstrate its effectiveness in a larger sample of PwD.

It should also be noted that the outcome evaluation did not include variables to assess the extent and level of care. The impact on the quality of life of PwD was also not directly assessed. These missing variables should be considered in future studies, always keeping the total number of cognitive and physical outcomes, as well as questions of usability and acceptability, within reasonable limits.

Another limitation relates to the general lack of conclusive evidence for the positive effects of exercise in the treatment of PwD (Chapter 2.2.3). Also, the RCT showed that it is not possible to prove effectiveness with statistical significance. Nevertheless, a significant number of participants were able to improve their physical and cognitive performance. This is already a success, especially in terms of disease progression. In addition, discussions with NHE and relatives, as well as the feedback or simply the smiling faces of the PwD have absolutely confirmed that exercise intervention has unquantifiable benefits. The definition of evidence in the IMF supports this by stating: „By the term evidence, we mean not only data from research studies as represented in the scientific literature but also the opinion and experience of community members and planners. In this way, theoretical and empirical evidence is brought to bear on meeting a health or social need.” (Bartholomew Eldredge et al., 2016, p. 8). This still allows us to speak of an evidence-based approach and does not contradict the definition within evidence-based medicine which states: „Evidence based medicine is the

conscientious, explicit, and judicious use of current best evidence in making decisions about the care of individual patients. The practice of evidence-based medicine means integrating individual clinical expertise with the best available external clinical evidence from systematic research (…) thoughtful identification and compassionate use of individual patients' predicaments, rights, and preferences in making clinical decisions about their care“ (Sackett et al., 1996, p. 71).

The evidence gap is multifactorial and difficult to bridge. Although the biology of adaptation to stimulation is essentially the same, it is difficult to 'administer' PA at the right level. PA has many important differences from other forms of treatment, such as medication or care, and therefore needs to be assessed differently. The administration of PA is context dependent because people depend on many factors, such as their own motivation, social support, provision, etc. Therefore, the environment and context in which the intervention is delivered is very important.

Finally, there is the critical question of why an application should be used by the NHE to do something outside of their actual job. Of course, it could be argued that with the nursing shortage, it is unlikely that nurses will have more time for exercise in the future. However, our experience shows that nurses are very receptive to these opportunities and that management in particular places a high value on exercise in nursing homes. It also shows that the benefits of exercise are tangible for NHE and that there is a high demand for education and training opportunities. Therefore, an app such as the InCoPE-App can make everyday life easier, bring new aspects to the job and possibly with appropriate adjustments support the health of the NHE.

7 Conclusion

The habilitation thesis aims to provide a digital exercise intervention for PwD that can be used by NHE to counteract the age- and disease-related cognitive and physical decline. The specific requirements for the digital application, and thus counter the current criticism of digital interventions, was to design and evaluate a theory- and evidence-based, user-centered digital intervention. The IMF was used to plan, design, and evaluate the digital exercise intervention.

Given the wide range of underlying topics, the theoretical part (see Chapter 2) provides an overview of three main topics: age- and disease-related cognitive and physical decline, effects of PA, and digital intervention planning for exercise interventions. These three main topics are summarized and deficits in existing research are identied, from which specific objectives are derived to achieve a theory- and evidence-based digital exercise intervention for PwD that is applicable to NHE and counteracts age- and disease-related cognitive and physical decline. The summary of research deficits formed the underlying aims addressed by the research articles forming this habilitation. The research articles are guided by the six steps of IMF and demonstrate the application of the IMF in the development of a digital exercise intervention.

The results of this habilitation thesis were developed along two research areas, the effects of PA and exercise on PwD and the planning and design of a digital exercise intervention. The findings in these research areas were recorded by allocating them to the evaluation levels of planning, structure, process and outcome evaluation. Regarding the effects of PA and exercise on PwD, it was found that a group-based multimodal exercise program developed specifically for PwD showed no statistically significant effects in a real-world scenario (research articles 1 and 2 in Chapter 5.1.1 and 5.1.2). The foundations of this multimodal exercise program are based on sports science findings on age-related physical and cognitive decline and the effects of PA (research article 3 and Chapter 2). Based on the findings that 28-40 % of participants were able to maintain balance, mobility, lower extremity strength and function and 23-49 % cognitive performance over 16 weeks and the observation that lower physical performance levels have greater effects (research articles 1 and 2), an approach to individualize the exercise intervention for PwD was developed (research article 6). This individualization approach was implemented in the digital exercise intervention and delivered by NHE through the InCoPE-App. The preliminary effects of the InCoPE-App were promising and showed an overall positive trend in global cognition, balance, mobility and lower limb

strength and function (research Article 12). However, due to the challenges during the COVID-19 pandemic, the sample size was too small for a final evaluation.

In the context of assessing the effects of PA on physical performance in PwD, it is important to consider the assessments used. Most physical performance tests have been developed for an aging population and not specifically for cognitive impairment. Even with dementia-specific adaptations (research articles 4 and 5), reliability, especially absolute reliability, remains a challenge.

The results of the second research area the planning and design of a digital exercise intervention, relate to the target group of end-users, in this case NHE. An online survey examined the general high affinity for technology as a determinant of subsequent technology acceptance and adoption (research article 8). Here, it was shown that the affinity for technology in nursing home management is rather low, which is important for the decision to implement of a digital intervention. The application of UX methods and general application planning combines the field of sports science and UX methods (research article 7). In addition, the development environment of the digital exercise intervention and the associated role of sports scientists were considered (research article 9) in order to be able to guide and control the development process well. The iterative development process of the digital exercise intervention was described in a study protocol (research article 10) and mixed methods results from end-users were generated as part of the process evaluation (research article 11). The feedback, which mainly related to the navigation logic and the comprehensibility of the app content, could be addressed in a further development iteration, which led to an improvement in the usability rating by the end users after 18 weeks of intervention.

Digitalization is having a major impact on the development of therapy and, therefore, exercise management. VR and AR approaches are already being used in practice. For PwD, this approach poses more challenges, which is why we conducted a study on the general feasibility of using VR and found it to be entirely feasible for PwD without any safety risk in terms of increasing the risk of falling (research article 13). There is a great potential for further research in this area. Both the design of exercise training with VR and thus a higher general cognitive load as well as the active stimulation of cognitive performance could be a promising approach. VR can also be used to increase individualisation. In addition, AR approaches could be extremely helpful in addressing current deficits related to the reliability of physical performance in PwD, but also in general cognitive impairment. Here, the use of AR can reduce cognitive load or bias (i.e., by displaying instructions or some form of gamification) and thus increase reliability, but also validity, as direct conclusions can be drawn about physical performance and the results are not biased by, for example, stimulus processing or language comprehension. In this context, other assistive technologies, such as exoskeletons, can be

used to support the musculoskeletal system, but alos to record physical performance in everyday situations rather than test situations. Exoskeletons may also allow for more personalized and contextualized exercise control. A comprehensive and validated record of physical performance can provide personalized support or even define deficits and training stimuli to increase exercise adaptations.

In this habilitation thesis, the IMF was applied to the planning and design of a digital exercise intervention. The application of the framework in this context was examined in detail through a literature review (Chapter 2.3.3), based on areas of application, but also specific adaptations to the digital context. Based on the own application and the literature review, an extension of the IMF was proposed. This extension was formulated based on the tasks within the six steps of the IMF and enriched with examples based on the literature review. This is a first approach to a standardized procedure for the entire planning, design, and development of digital exercise interventions, which certainly needs further refinements. However, the opportunity for future research may lie in changing or improving the much-debated evaluation of digital interventions through a standardized process.

In the growing market of digital interventions that largely consider and incorporate the lifestyle factor of PA and exercise, it is also important to ensure that exercise science is properly integrated. This is important because the positive effects of PA and exercise can only be achieved through the correct integration of exercise and movement science. At the same time, it is important to interpret the data so that it can be fed back into practice. This leads to an understanding of the role of sports science within software development as domain experts. This in turn requires a basic understanding of software engineering and agile working, as well as familiarity with UX methods and behavioral change techniques. Exercise and movement science expertise will remain central. In this context, however, the training of sports scientists should also be reconsidered in order to improve access to the digital health market and thus to the jobs located there, but also to improve the digital health market's understanding of the importance of sports science.

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Bettina Barisch-Fritz studierte Sportwissenschaft an der Universität Tübingen und promovierte im Bereich Biomechanik/Trainingswissenschaft an der TU Chemnitz mit Auszeichnung. Nach Tätigkeiten in der Sportmedizin Tübingen sowie Forschungsaufenthalten arbeitet sie seit 2016 am Institut für Sport und Sportwissenschaft des KIT. Ihre Forschung untersucht Bewegung als Ressource für kognitiv-motorische Entwicklung über die Lebensspanne – von der frühen Kindheit bis zum hohen Alter, besonders bei Menschen mit Demenz. Methodisch verknüpft sie multimodales Training, Versorgungsforschung und pädagogische Konzepte mit Schwerpunkt digitaler Bewegungsversorgung und leitete zahlreiche Projekte zur Entwicklung, Implementierung und Evaluation von Bewegungsprogrammen in diversen Settings. Durch langjährige Praxiserfahrung in Präventionssport, Sporttherapie und Rehabilitation sowie Engagement in kommunalen, nationalen und internationalen Netzwerken verbindet sie wissenschaftliche Exzellenz mit alltagsnaher Wirksamkeit.

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