# The effectiveness of digital and conventional rehabilitation and prevention programs: Impact on work ability, physical and mental health in orthopedic and occupational contexts

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# Summary

Demographic change and population ageing pose major challenges for health and social systems in Germany. The increasing prevalence of chronic diseases, particularly musculoskeletal and cardiovascular conditions, threatens both health systems and the sustainability of the workforce. Within this context, the German Pension Insurance plays a central role, guided by its principles of "rehabilitation before pension" and "rehabilitation before care", making prevention and rehabilitation essential instruments to maintain employability. However, conventional programs face persistent challenges such as limited access, declining adherence after discharge, and waning treatment effects. Digital programs have emerged as potential solutions that may overcome barriers of time and place, provide scalable support, and sustain long-term engagement. Yet, there is still a lack of robust empirical evidence in Germany comparing the effectiveness of digital and conventional formats with respect to work ability, physical health, and mental health.

A decade of international studies has highlighted the potential of digital health interventions, but the field remains in an early phase of evaluation within the German rehabilitation and prevention context. Evidence from other countries cannot be directly transferred due to the structural particularities of the German system, where the pension insurance is the largest rehabilitation provider. This is why the overarching aim of this dissertation was to systematically compare digital and conventional programs in prevention and rehabilitation aftercare. The analyses focused on work ability, physical health, and mental health, with particular emphasis on the sustainability of intervention effects and the role of moderating factors such as age, gender, and employment status.

This dissertation comprises three empirical studies. The first study compared a digital prevention program with the conventional RV Fit program among employees with initial impairments. Both programs improved work ability and mental health, although no significant changes were observed in physical health. Younger employees benefited more strongly from the digital format, whereas older participants improved more under the conventional program. The second study evaluated digital versus conventional rehabilitation aftercare (digIRENA vs. IRENA) for orthopedic patients, with a control group receiving no structured aftercare. Results showed improvements in physical and mental health across all groups, with the most pronounced gains in the digital format, although effects declined once structured support ended. The third study focused on work ability in the same population, demonstrating that all groups improved over time but that the digital format led to steeper early gains. These advantages were particularly evident among younger and unemployed patients, highlighting the role of individual characteristics in shaping intervention effectiveness.

Taken together, these studies demonstrate that digital programs are at least as effective as conventional ones in prevention and rehabilitation, and in some respects superior, particularly for mental health and early improvements in work ability. However, the sustainability of effects remains a challenge for both formats, pointing to the need for hybrid and personalized models that integrate digital flexibility with interpersonal support. The dissertation highlights the importance of tailoring interventions to demographic subgroups, especially regarding age, gender, and employment status, and suggests that hybrid models could maximize the reach and effectiveness of services across heterogeneous populations.

In conclusion, this dissertation contributes to closing critical evidence gaps in the German rehabilitation and prevention system. It provides robust comparative data that not only advance scientific understanding of digital versus conventional formats but also inform the practical design of rehabilitation services. The findings underline the potential of digital interventions to support the mission of the German Pension Insurance in preserving work ability and health in the face of demographic change. At the same time, they call for continued innovation in hybrid approaches and long-term support strategies to sustain treatment effects and ensure equitable access across all population groups.

# Zusammenfassung

Der demografische Wandel und die Alterung der Bevölkerung stellen erhebliche Herausforderungen für die Gesundheits- und Sozialsysteme in Deutschland dar. Die zunehmende Verbreitung chronischer Erkrankungen, insbesondere muskuloskelettaler und kardiovaskulärer Leiden, gefährdet sowohl die Gesundheitssysteme als auch die nachhaltige Erwerbsfähigkeit der Bevölkerung. In diesem Kontext kommt der Deutschen Rentenversicherung eine zentrale Rolle zu. Geleitet von den Prinzipien „Reha vor Rente“ und „Reha vor Pflege“ sind Prävention und Rehabilitation wesentliche Instrumente zur Sicherung der Erwerbsfähigkeit. Konventionelle Programme sehen sich jedoch anhaltenden Problemen gegenüber, wie eingeschränktem Zugang, nachlassender Adhärenz nach der Entlassung und abnehmender Wirksamkeit der Behandlung. Digitale Programme haben sich als potenzielle Lösungen herauskristallisiert, die Barrieren von Zeit und Ort überwinden, skalierbare Unterstützung bieten und langfristiges Engagement fördern können. Dennoch fehlt es in Deutschland bislang an belastbarer empirischer Evidenz, die die Wirksamkeit digitaler und konventioneller Formate im Hinblick auf Arbeitsfähigkeit, körperliche und psychische Gesundheit vergleicht.

Zehn Jahre internationaler Studien haben das Potenzial digitaler Gesundheitsinterventionen aufgezeigt, doch befindet sich das Forschungsfeld im deutschen Rehabilitations- und Präventionskontext noch in einer frühen Phase der Evaluation. Ergebnisse aus anderen Ländern lassen sich aufgrund der strukturellen Besonderheiten des deutschen Systems, in dem die Rentenversicherung der größte Rehabilitationsträger ist, nicht direkt übertragen. Vor diesem Hintergrund bestand das übergeordnete Ziel dieser Dissertation darin, digitale und konventionelle Programme in Prävention und Reha-Nachsorge systematisch zu vergleichen. Die Analysen konzentrierten sich auf Arbeitsfähigkeit, körperliche und psychische Gesundheit, mit besonderem Augenmerk auf die Nachhaltigkeit der Interventionseffekte sowie die Rolle moderierender Faktoren wie Alter, Geschlecht und Beschäftigungsstatus.

Die Dissertation umfasst drei empirische Studien. Die erste Studie verglich ein digitales Präventionsprogramm mit dem konventionellen RV Fit-Programm bei Beschäftigten mit ersten gesundheitlichen Beeinträchtigungen. Beide Programme verbesserten Arbeitsfähigkeit und psychische Gesundheit, während für die körperliche Gesundheit keine signifikanten Veränderungen festgestellt wurden. Jüngere Beschäftigte profitierten stärker vom digitalen Format, während ältere Teilnehmende größere Verbesserungen im konventionellen Programm erzielten. Die zweite Studie untersuchte die digitale gegenüber der konventionellen Reha-Nachsorge (digIRENA vs. IRENA) bei orthopädischen Patientinnen und Patienten, ergänzt um eine Kontrollgruppe ohne strukturierte Nachsorge. Die Ergebnisse zeigten Verbesserungen der körperlichen und psychischen Gesundheit in allen Gruppen, wobei die größten Zuwächse im digitalen Format beobachtet wurden; diese Effekte nahmen jedoch nach Beendigung der strukturierten Nachsorge wieder ab. Die dritte Studie fokussierte auf die Arbeitsfähigkeit derselben Population und zeigte, dass alle Gruppen im Zeitverlauf Verbesserungen erzielten. Das digitale Format führte jedoch zu steileren Steigerungen der Arbeitsfähigkeit. Diese Vorteile waren besonders bei jüngeren und arbeitslosen Personen ausgeprägt, was die Bedeutung individueller Merkmale für die Wirksamkeit von Interventionen unterstreicht.

Zusammenfassend zeigen die Studien, dass digitale Programme mindestens ebenso wirksam sind wie konventionelle und in einigen Bereichen überlegen, insbesondere in Bezug auf psychische Gesundheit und frühe Verbesserungen der Arbeitsfähigkeit. Allerdings bleibt die Nachhaltigkeit der Effekte für beide Formate eine Herausforderung, was die Notwendigkeit hybrider und personalisierter Modelle unterstreicht, die digitale Flexibilität mit interpersonaler Unterstützung verbinden. Die Dissertation hebt die Bedeutung einer zielgruppenspezifischen Anpassung der Interventionen hervor, insbesondere in Bezug auf Alter, Geschlecht und Beschäftigungsstatus, und legt nahe, dass hybride Modelle die Reichweite und Wirksamkeit der Angebote in heterogenen Populationen maximieren können.

Abschließend trägt diese Dissertation dazu bei, zentrale Evidenzlücken im deutschen Rehabilitations- und Präventionssystem zu schließen. Sie liefert belastbare Vergleichsdaten, die nicht nur das wissenschaftliche Verständnis digitaler und konventioneller Formate erweitern, sondern auch die praktische Gestaltung von Rehabilitationsleistungen informieren. Die Ergebnisse unterstreichen das Potenzial digitaler Interventionen, den Auftrag der Deutschen Rentenversicherung zur Erhaltung von Arbeitsfähigkeit und Gesundheit im Zuge des demografischen Wandels zu unterstützen. Zugleich weisen sie auf die Notwendigkeit kontinuierlicher Innovation hybrider Ansätze und langfristiger Unterstützungsstrategien hin, um Behandlungseffekte zu sichern und einen gerechten Zugang über alle Bevölkerungsgruppen hinweg zu gewährleisten.

# List of Publications

## PhD Thesis Research

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# Chapter I – General Introduction

## Background and Problem Definition

Demographic change is one of the most profound societal challenges in Germany and other industrialized nations (Schön, 2023). The population is aging rapidly as life expectancy continues to rise while birth rates remain persistently low. As life expectancy increases and birth rates remain low, the working-age population declines while the number of older adults requiring care rises (Vanella et al., 2022). As a consequence, chronic conditions, particularly musculoskeletal and cardiovascular diseases, are becoming more prevalent, contributing to long-term impairments in functional health and quality of life (Heidemann et al., 2021). These trends not only strain healthcare systems but also pose significant risks to labor market sustainability, as maintaining work ability and extending healthy life years are becoming central policy and public health priorities (Schön, 2023).

The demographic trends of an aging population and a shrinking workforce directly translate into rising demands on healthcare systems, particularly in the domains of prevention and rehabilitation (Nowossadeck, 2019). With chronic and musculoskeletal diseases increasingly prevalent among older adults, the need for medical rehabilitation to preserve or restore functional capacity is steadily growing (Porst et al., 2022). At the same time, preventive interventions gain importance in delaying disease onset and reducing the burden of disability (Schloemer et al., 2021). These developments place healthcare providers and social insurance systems under mounting pressure to deliver effective and sustainable programs that not only address acute health impairments but also support long-term maintenance of work ability (Nowossadeck et al., 2020). In Germany, this challenge is especially critical for the pension insurance system, which is mandated to secure labor force participation. Consequently, ensuring timely and efficient access to preventive and rehabilitative services has become a cornerstone of both healthcare provision and labor market policy.

Within this context, the German Pension Insurance (Deutsche Rentenversicherung, DRV) plays a central role in safeguarding the employability of the working-age population (Schimmang, 2022). Its mandate is grounded in the principles of "rehabilitation before pension" (Reha vor Rente) and "rehabilitation before care" (Reha vor Pflege), which emphasize restoring functional capacity and delaying disability or dependency through timely intervention (Sewöster, 2023). These guiding principles reflect the understanding that effective rehabilitation not only benefits individuals by preserving health and work ability, but also alleviates the long-term financial burden on the pension and care systems. By investing in medical, psychosomatic, and preventive rehabilitation programs, the DRV seeks to extend participation in the labor force, reduce premature retirement due to illness, and prevent the early onset of nursing care needs. In 2023 alone, the DRV devoted 7.64 billion euros in gross expenditures to rehabilitation, with more than 6 billion euros for medical rehabilitation and over 1.2 billion euros for vocational participation services (DRV, 2024c). Collectively, these indicators substantiate the DRV's position as Germany's largest rehabilitation provider and a core actor at the interface of health care and labor market policy.

## Challenges for Prevention and Rehabilitation

Despite their central role in the German healthcare system, conventional rehabilitation and prevention programs face several limitations that restrict their long-term effectiveness (Zimmer et al., 2022). Participation is often hindered by accessibility barriers, including geographical distance to specialized clinics, time constraints related to work and family obligations as well as financial or logistical difficulties associated with repeated travel. Even when individuals complete an inpatient or outpatient program, adherence to prescribed lifestyle changes and therapeutic routines tends to decline over time once the structured clinical setting is left behind. Empirical studies have shown that the positive effects of rehabilitation on physical health, mental well-being, and work ability frequently diminish within months after discharge if no structured aftercare is pursued (Schilling, 2023). This pattern of waning effectiveness highlights a critical gap in sustaining behavioral change and underscores the need for more flexible, scalable, and patient-centered intervention models that maintain rehabilitation outcomes in daily life.

In response to these limitations, digital interventions have emerged as a promising complement and, in some contexts, an alternative to conventional rehabilitation programs (Sewöster, 2023). Digital formats such as tele-rehabilitation platforms, mobile health applications and online aftercare programs including IRENA digital or Psy-RENA digital provide scalable and flexible delivery of therapeutic content independent of time and location. By enabling patients to

engage in exercise training, psychological counseling or educational modules from home, these interventions reduce access barriers and allow for greater integration into everyday routines. In addition, digital programs can provide ongoing support and monitoring beyond the fixed duration of inpatient or outpatient rehabilitation, which helps to strengthen adherence and sustain behavioral change. Early evidence from international studies suggests that such interventions may improve participation rates and help maintain therapeutic gains over longer periods, positioning them as a valuable tool to enhance the continuity and efficiency of rehabilitation and prevention services (Agostini et al., 2015).

While digital approaches show considerable potential, the evidence regarding their comparative effectiveness relative to conventional rehabilitation remains limited. In particular, little is known about their long-term impact on sustained health outcomes and the preservation of work ability, which are central goals of the German rehabilitation system. Compared with the growing body of international literature, the evidence base in Germany is still sparse. Moreover, findings from other health care contexts cannot be directly transferred, since the German system is structurally distinct from those of many Anglo-Saxon countries where much of the existing research has been conducted (Agostini et al., 2015). The strong institutional role of the pension insurance and the legal principles of rehabilitation before pension and rehabilitation before care set Germany apart, underscoring the need for nationally grounded research to evaluate the specific effectiveness and sustainability of digital rehabilitation interventions (Sewöster, 2023).

# Goals of the Dissertation

The overarching aim of this dissertation is to investigate and compare the effectiveness of digital and conventional interventions in the fields of prevention and rehabilitation. By systematically examining both formats within the framework of the German health care and pension insurance system, the study seeks to contribute to a more comprehensive understanding of their respective potentials and limitations in addressing the challenges posed by demographic change.

The evaluation focuses on work ability, physical and mental health, and explicitly addresses the sustainability of effects over defined follow up periods. Concerning the topic of prevention, the dissertation determines the effects of digital compared with conventional programs on work ability as well as physical and mental health among employees with initial impairments at program end and follow up. In rehabilitation aftercare, the dissertation first tests whether digital aftercare implemented as digIRENA sustains improvements in physical and mental health to a greater or equal extent than conventional IRENA across follow up assessments in orthopedic patients. It then compares changes in work ability among patients receiving digIRENA, conventional IRENA, or no organized aftercare. Across all analyses, the dissertation examines effect heterogeneity by age, gender, employment status, and baseline impairment in order to identify subgroups for whom specific formats are particularly effective. As an exploratory objective, the dissertation also describes adherence and engagement in digital and conventional formats and investigates their association with primary outcomes over time to inform interpretation of sustainability. Together, these goals establish the foundation for an evidence-based comparison of digital and conventional approaches, with the potential to inform both scientific debate and practical decision-making in the further development of rehabilitation and prevention services in Germany.

# Significance for Science and Practice

From a scientific perspective, this dissertation contributes to closing a critical evidence gap by providing robust longitudinal data and controlled comparative analyses of digital and conventional interventions in prevention and rehabilitation. Through the integration of multiple outcome dimensions, including physical and mental health as well as work ability, the study generates a more comprehensive understanding of intervention effectiveness over time. In addition, by examining moderating factors such as age, gender and employment status, the dissertation offers insights into the mechanisms and boundary conditions that shape the success of different intervention formats. These findings not only extend the empirical foundation of rehabilitation research in Germany but also contribute to understanding the effects of demographic factors and the resulting challenges in the health care system.

From a practical perspective, the dissertation provides evidence that supports informing health policy and clinical practice by clarifying which patient groups benefit most from digital or conventional programs. Such knowledge is essential for guiding resource allocation, ensuring that rehabilitation services are tailored to the needs of different populations, and avoiding inefficient use of limited capacities. The findings can support insurers and providers in designing intervention strategies that maximize effectiveness while remaining cost-efficient, for example by integrating

digital components into conventional care or by targeting specific subgroups with tailored program formats. In this way, the dissertation has the potential to contribute to further development of a differentiated and sustainable rehabilitation system that responds to demographic change and strengthens occupational reintegration. The following sections build on these foundations by contextualizing the role of prevention and rehabilitation within the German Pension Insurance system, elaborating the theoretical and conceptual frameworks of health and work ability, and formulating the central research questions and hypotheses that guide the empirical analyses of this dissertation.

# Prevention and Rehabilitation in the German Pension Insurance

Prevention and rehabilitation in Germany are supported by a broad institutional framework. In addition to the German Pension Insurance, statutory health insurance funds, statutory accident insurance, and statutory long-term care insurance play important roles in financing and delivering preventive and rehabilitative measures (Hetzel et al., 2023). Furthermore, federal states, municipalities, and a variety of foundations provide additional support through regional programs, public health initiatives, and disease-specific interventions. A comprehensive overview of all these institutions would exceed the scope of this dissertation. The following section therefore concentrates exclusively on the promotion of prevention and rehabilitation within the framework of the German Pension Insurance. This focus is chosen because the DRV constitutes the primary institutional context of the empirical studies presented in this dissertation and plays a pivotal role in maintaining employability and work ability in Germany (DRV, 2024c).

# Historical and Legal Context of Rehabilitation in the German Pension Insurance

The origins of rehabilitation in the German social insurance system can be traced back to the late nineteenth century, when Chancellor Otto von Bismarck established the foundations of statutory health and accident insurance (Eghigian, 2000). From the outset, these schemes were not limited to compensating for income loss but also included measures to restore health and the capacity to work. In the context of occupational accidents, rehabilitation was conceived as a means of enabling injured workers to return to productive employment rather than becoming permanently dependent on welfare or pensions. This early integration of medical care and vocational reintegration marked a paradigm shift in social policy, as it placed emphasis on preserving work ability and social participation. Over the course of the twentieth century, these principles became more systematically embedded in the statutory pension insurance, where rehabilitation evolved into a central instrument for preventing disability pensions and maintaining employability.

The rehabilitation mandate of the German Pension Insurance developed significantly during the twentieth century as demographic and economic conditions changed. After the Second World War, the rising burden of chronic illnesses and long-term impairments highlighted the need for structured rehabilitation services beyond acute medical care. In response, the DRV gradually expanded its role from a pure pension provider to a comprehensive institution responsible for safeguarding employability (Wehner, 2019). This evolution was codified in the Social Code Book (Sozialgesetzbuch VI; SGB VI), which firmly established the principle of "rehabilitation before pension" as a legal obligation. Under this framework, rehabilitation is not considered a discretionary benefit but a statutory entitlement for insured persons whose ability to work is threatened by illness or disability. Over time, the DRV has built an extensive network of its own rehabilitation clinics and contractual arrangements with specialized providers, thereby institutionalizing rehabilitation as a cornerstone of its social insurance mandate.

The legal foundations of rehabilitation within the German social insurance system are anchored in several core statutes. Social Code Book VI (SGB VI) defines the DRV's responsibility to provide rehabilitation benefits whenever employability is at risk, thereby operationalizing the guiding principle of "rehabilitation before pension" (Kreikebohm et al., 2008). Complementing this, Social Code Book IX (SGB IX) establishes a cross-sectoral framework for rehabilitation and participation, ensuring coordination among different insurance branches and creating legally binding procedures such as the "single application" principle to guarantee seamless access to services (Knoche, 2025). The Präventionsgesetz of 2015 further strengthened this legal architecture by expanding preventive mandates across all branches of social insurance and introducing a National Prevention Strategy to coordinate health promotion efforts. Together, these laws create a comprehensive framework in which rehabilitation is not only an individual entitlement but also a collective obligation of the social insurance system to preserve work ability and social participation.

# The DRV's Mandate: "Rehabilitation before Pension"

The central mission of the German Pension Insurance in the field of rehabilitation is the preservation and restoration of work ability. This principle reflects the understanding that gainful employment is not only the foundation of individual economic security but also a key determinant of social integration and quality of life. By focusing on maintaining employability, the DRV aims to prevent premature exit from the labor market and reduce the long-term burden on the pension system. Rehabilitation is therefore conceived as an investment in human capital, with the goal of enabling insured individuals to continue participating in working life for as long as possible. This mission guides the design, funding, and delivery of rehabilitation services and underpins the DRV's motto "rehabilitation before pension."

Rehabilitation plays a strategic role in the DRV's broader mission of safeguarding workforce participation and ensuring the financial stability of the pension system. Every case in which a worker's health is stabilized or restored through rehabilitation represents not only a gain in individual quality of life but also a reduction in the number of disability pensions granted. In this sense, rehabilitation is both a social and an economic instrument: it prevents individuals from becoming permanently dependent on pension benefits while at the same time maintaining their contribution to the financing of the system. With demographic change leading to an aging workforce and rising prevalence of chronic diseases, the importance of effective rehabilitation has grown significantly. By enabling workers to remain active in the labor market, rehabilitation helps mitigate the shrinking labor force and supports the sustainability of the social insurance system.

# Medical Rehabilitation in the DRV

The German Pension Insurance offers a broad spectrum of rehabilitation services designed to address diverse health conditions and individual needs. Inpatient rehabilitation remains the most frequently provided format, typically delivered in specialized clinics where medical, therapeutic, and psychosocial interventions are combined in a structured residential program. At the same time, outpatient rehabilitation has gained importance, particularly for patients with stable social support and less severe health impairments, as it allows them to remain in their home and work environments while receiving comprehensive therapy. A further development has been the expansion of multimodal rehabilitation programs, which integrate medical treatment, physical training, psychological counseling, and occupational therapy in a coordinated approach. These multimodal interventions are especially relevant for chronic conditions such as musculoskeletal disorders or mental health problems, where complex interactions between physical, psychological, and social factors determine work ability and long-term outcomes.

The majority of rehabilitation services provided by the DRV are directed toward health conditions that most frequently threaten work ability. Musculoskeletal disorders, such as chronic back pain, joint diseases, and degenerative spinal conditions, constitute the largest diagnostic group, reflecting their high prevalence among the working-age population and their significant impact on functional capacity. Cardiovascular diseases, including coronary heart disease and heart failure, form another major indication, as they often require structured rehabilitation to restore physical performance and prevent recurrence. A third key group comprises psychosomatic and mental health disorders, such as depression, anxiety, or stress-related syndromes, which have grown markedly in importance over the past two decades and now represent one of the leading causes of long-term work incapacity. By targeting these common indications, DRV rehabilitation programs aim to address the conditions most responsible for disability pensions and prolonged absence from the labor market.

The organizational infrastructure of the DRV's rehabilitation system combines its own network of specialized rehabilitation clinics with a broad range of external partner facilities. The DRV operates a number of its own rehabilitation centers across Germany, which serve as competence hubs and model institutions for implementing innovative therapeutic concepts and quality standards. At the same time, the majority of services are delivered through contracts with independent rehabilitation providers, including hospitals, outpatient centers, and specialized clinics. These partnerships allow the DRV to ensure regional accessibility and to cover the full range of medical indications, while maintaining uniform quality requirements through strict accreditation, monitoring, and evaluation procedures. This dual structure provides both stability, through DRV-owned institutions, and flexibility, through cooperation with external providers, enabling the system to respond effectively to changing needs and regional demand.

# Occupational Rehabilitation and Reintegration

In addition to classical medical rehabilitation, the DRV has increasingly expanded its portfolio to include workplace-focused preventive interventions that address health risks before they result in prolonged incapacity. These programs are designed for employed individuals who show early signs of health-related work limitations, such as musculoskeletal complaints, stress symptoms, or reduced resilience, but who are not yet unable to work. Typically, they combine medical assessments with targeted training modules on physical activity, ergonomics, stress management, and lifestyle modification, often delivered in cooperation with employers and occupational health services. By integrating workplace-related factors and focusing on maintaining employability, these interventions bridge the gap between primary prevention and rehabilitation. They reflect the DRV's strategic orientation toward preserving work ability proactively rather than reacting only after significant health deterioration has occurred.

Beyond preventive courses, the DRV provides a wide spectrum of vocational rehabilitation measures that directly support continued labor market participation. These include retraining programs and further qualification for individuals whose health limitations prevent them from continuing in their original profession. In addition, ergonomic adaptations at the workplace, such as specialized equipment, modified work processes, or adjustments to workload and environment, are funded to enable employees to maintain employment despite functional restrictions. Where reintegration requires temporary financial support, the DRV may grant wage subsidies to employers who hire or retain workers with reduced performance capacity. Together, these instruments illustrate the holistic approach of the DRV's rehabilitation system, which extends beyond medical treatment to encompass the broader social and occupational dimensions of health, with the explicit aim of securing employability and preventing premature exit from the workforce.

The effectiveness of workplace-focused rehabilitation measures depends strongly on close cooperation between the DRV, employers, and employment agencies. Employers play a key role in identifying employees at risk of health-related work limitations and in facilitating the implementation of workplace adaptations or flexible working arrangements. Employment agencies, in turn, contribute expertise in vocational guidance, placement, and support for retraining programs, ensuring that individuals whose previous occupations are no longer feasible can find suitable alternatives. Through formal agreements and collaborative projects, the DRV coordinates these stakeholders to create seamless rehabilitation pathways that integrate medical, social, and occupational interventions. This cooperative framework not only enhances the sustainability of rehabilitation outcomes but also fosters a shared responsibility for maintaining employability and reducing the economic burden of disability.

# Preventive Programs in the DRV

In recent years, the DRV has expanded its activities beyond classical rehabilitation to include preventive interventions aimed at workers who show early signs of health-related work impairments. These programs are designed to intervene before chronic conditions develop or existing health problems result in long-term incapacity to work. Typically offered as modular, multimodal courses, they combine elements of physical activity, health education, stress management, and lifestyle modification. Participation is voluntary and often initiated by physicians, employers, or the insured themselves, with the goal of stabilizing health and maintaining work ability. By targeting individuals at risk, such early intervention programs embody the preventive orientation of the German pension insurance system and reflect the principle of "prevention before rehabilitation, rehabilitation before pension".

The expansion of prevention within the DRV was initially shaped by pioneering pilot projects that explored new approaches to sustaining employability. A prominent example is the Betsi program (**Be**schäftigungsfähigkeit **t**eilhabeorientiert **si**chern), which was designed as a workplace-related intervention to stabilize work ability and prevent early exit from the labor force (DRV, 2008). Betsi focused on individuals already showing health-related risk factors but not yet in need of full rehabilitation. The program combined medical, psychosocial, and occupational elements, such as physical exercise, stress regulation techniques, and counseling for work-related challenges. Evaluations of Betsi indicated that short, targeted interventions could delay or even avert the onset of disability, reduce sick leave, and enhance participants' perceived work ability. This made Betsi a pioneering step toward embedding preventive approaches more firmly into the DRV's portfolio, while also providing valuable insights into the design and evaluation of structured prevention programs.

Building on these experiences, the DRV launched RV Fit as a nationwide standard program for preventive health promotion among insured persons (DRV, 2020). Unlike the more experimental Betsi projects, RV Fit is embedded in

the regular service spectrum of the DRV and thus accessible to a broad population. It consists of modular interventions addressing physical activity, nutrition, stress management, and health education, delivered in a multimodal and group-based format. A central feature of RV Fit is its low-threshold design: participation is voluntary, free of charge, and requires only a medical assessment of risk factors rather than manifest illness. The program is explicitly oriented toward the working population, with the objective of strengthening health resources, maintaining work ability, and preventing long-term disability. In this sense, RV Fit reflects a paradigmatic shift in the DRV's strategy from a system primarily focused on rehabilitation after illness to one that actively promotes prevention at an earlier stage. Its broad implementation, supported by the 2015 Prevention Act, has positioned RV Fit as a flagship initiative of German social insurance in the field of occupational health promotion.

The growing emphasis on preventive programs such as Betsi and RV Fit must also be understood against the backdrop of demographic change and rising demands on working life. With an aging workforce, longer employment trajectories, and increasing psychosocial and physical stressors in many occupations, the preservation of work ability has become a central societal and economic challenge. By targeting insured persons at an earlier stage and supporting them in maintaining their health resources, the DRV contributes not only to individual well-being but also to the long-term stability of the social insurance system. Prevention thereby complements traditional rehabilitation in ensuring that as many people as possible remain active, employable, and integrated in working life, despite the demographic and structural pressures shaping today's labor markets. In this way, the DRV's expanding prevention mandate represents both a response to and a proactive strategy for managing the profound changes in Germany's workforce and health landscape.

# Aftercare Services in the German Pension Insurance

Aftercare services (Reha-Nachsorge) provided by the German Pension Insurance represent a structured continuation of medical rehabilitation and are designed to consolidate and sustain the therapeutic gains achieved during inpatient or outpatient programs. Their overarching purpose is to strengthen the physical, psychological, and social resources of rehabilitants, thereby preventing relapses, reducing the risk of recurrent health impairments, and restoring or maintaining work ability in the long term. By ensuring that exercises, coping strategies, and health behaviors learned during rehabilitation are transferred into everyday life, aftercare serves as a bridge between intensive treatment in a rehabilitation setting and the challenges of daily working and private life.

The legal basis of aftercare lies primarily in §17 of the Social Code Book VI (SGB VI), which regulates the rehabilitation responsibilities of the pension insurance, and in §64 of the Social Code Book IX (SGB IX), which anchors specific provisions for rehabilitation sport and functional training. According to these provisions, aftercare is a statutory benefit rather than a discretionary service, granted when rehabilitation goals have been largely achieved but continued structured support is necessary to secure lasting success. Standardized nationwide aftercare programs ensure that all rehabilitants have access to appropriate services, independent of their place of residence or the responsible DRV branch. This legal framework reflects the principle of "rehabilitation before pension" and underscores the DRV's obligation not only to provide acute rehabilitation but also to safeguard its outcomes through structured follow-up care.

Aftercare programs of the German Pension Insurance are characterized by their standardized structure, which ensures continuity of rehabilitation while allowing adaptation to individual circumstances. As a rule, aftercare begins within three months following the completion of an inpatient or outpatient rehabilitation program, thereby creating a seamless transition from intensive treatment back into everyday life. The programs are time-limited, usually extending over a period of six to twelve months, with a typical scope of 24 to 26 sessions delivered once or twice per week. This regularity is intended to stabilize physical fitness, strengthen coping skills, and foster sustainable behavioral change.

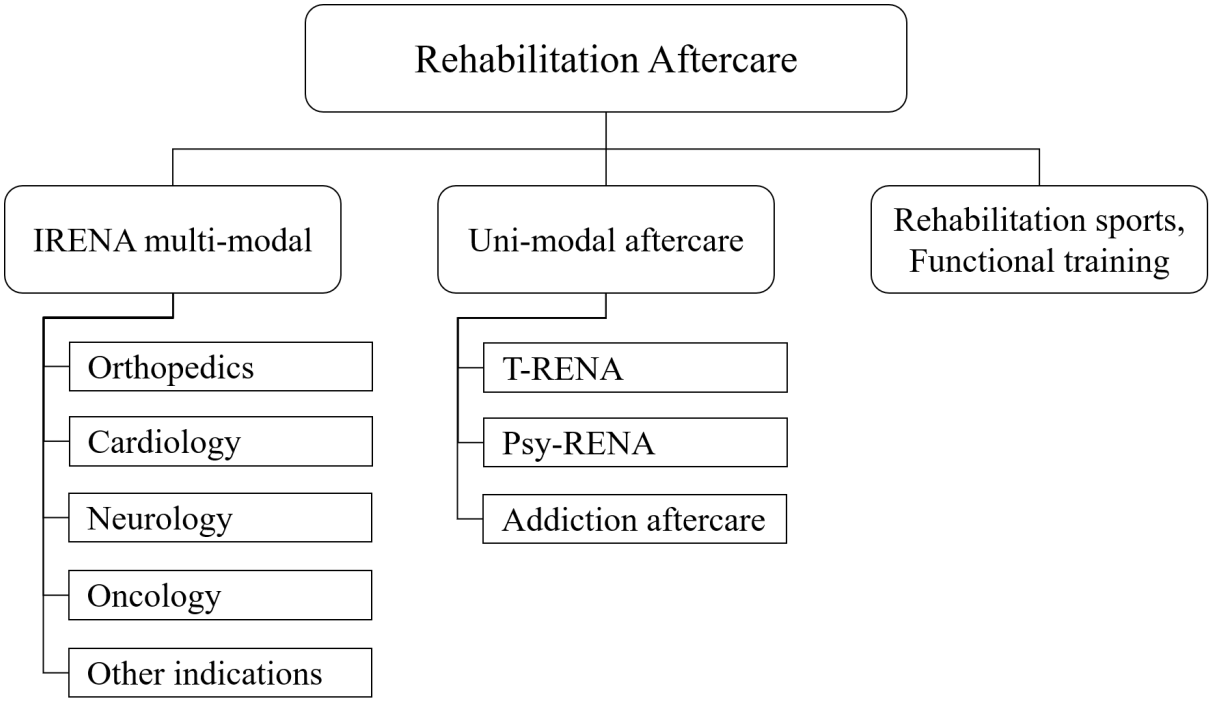
Most aftercare services are group-based, combining therapeutic exercise, education, and peer support. They are designed to integrate into everyday routines, enabling participants to continue therapeutic activities while managing their occupational and social responsibilities. Beyond standardized nationwide offers, additional regional or facility-specific aftercare programs may exist. These are often implemented as model projects by individual pension insurance providers or rehabilitation facilities, with the aim of testing innovative strategies for long-term care. Such regionally restricted programs may later evolve into nationally recognized core services if their effectiveness is demonstrated.

In addition to conventional face-to-face formats, rehabilitants can access supplementary measures such as rehabilitation sport and functional training. These interventions are recognized as aftercare services and are typically offered for six

months, extendable up to twelve months, with one to two sessions per week. By embedding physical activity and functional exercises into daily life, these services contribute to the preservation of mobility, endurance, and work ability, while also promoting social participation and self-management.

To secure the long-term effects of rehabilitation, the German Pension Insurance has established a set of standardized aftercare programs that are available nationwide (see Figure 1). These programs differ in their therapeutic focus, intensity, and setting but share the overarching aim of consolidating rehabilitation outcomes, supporting reintegration into working life, and preventing relapse (DRV, 2024b; Sewöster, 2019).

Figure 1: Range of rehabilitation aftercare services offered by the DRV




IRENA (Intensivierte Rehabilitationsnachsorge) represents the multimodal aftercare format, which combines elements from different therapeutic domains such as physiotherapy, occupational therapy, psychological counseling, and health education (DRV, 2021a). IRENA is carried out in rehabilitation facilities by interdisciplinary teams and is designed for patients with complex health problems requiring coordinated interventions across multiple domains (Lamprecht et al., 2012).

T-RENA (Trainingstherapeutische Reha-Nachsorge) is targeted at individuals with musculoskeletal impairments and emphasizes equipment-based training (DRV, 2021b). The program aims to improve strength, mobility, endurance, and coordination, thereby reducing pain and enhancing physical work capacity (Sewöster, 2019). T-RENA typically consists of 26 training sessions, delivered twice weekly in group settings, though it can also be offered as an individual service if necessary.

Psy-RENA (Reha-Nachsorge bei psychischen Erkrankungen) addresses individuals with mental health disorders such as depression, anxiety, or stress-related syndromes (DRV, 2024a). Conducted primarily in group settings, Psy-RENA focuses on strengthening coping strategies, conflict resolution skills, and social competencies, while also addressing workplace-related challenges (Friedrich & Hepp, 2020). Standard participation includes 25 group sessions supported by individual intake and closing consultations.

Addiction Aftercare (Ger. Sucht-Nachsorge) is tailored to patients recovering from dependency disorders. It provides structured group and individual sessions aimed at consolidating abstinence, stabilizing new health behaviors, and

fostering social reintegration. Typically, 20 group sessions and two additional sessions for relatives or close contacts are offered over a six-month period (DRV, 2024b).

Finally, Rehabilitation Sports and Functional Training constitute complementary aftercare services anchored in §64 SGB IX. Rehabilitation sports include group-based physical activity such as gymnastics, swimming, or athletics, while functional training provides therapeutic exercises to preserve or restore specific bodily functions. Both formats are designed to strengthen endurance, mobility, and self-efficacy, and are usually offered once or twice per week for up to twelve months (DRV, 2024b).

# Utilization and Challenges of Prevention, Rehabilitation, and Aftercare

Although the German Pension Insurance offers a wide spectrum of preventive programs, rehabilitation measures, and structured aftercare, utilization remains uneven across the continuum of services. Participation in preventive programs such as Betsi or RV Fit is still limited, often due to low awareness among employees and employers, as well as competing work and family responsibilities. Rehabilitation services, in contrast, are widely accessed but face challenges related to regional disparities, waiting times, and varying levels of patient adherence. Aftercare programs show the lowest uptake, with only about 14% of eligible rehabilitants participating in 2019, despite their recognized importance for sustaining rehabilitation outcomes (DRV, 2023b).

Several structural and individual barriers contribute to this underutilization. On the individual level, lack of motivation, limited health literacy, and difficulties integrating program requirements into daily routines are common obstacles. From a structural perspective, insufficient coordination between different service providers, regional gaps in provision, and rigid program formats reduce accessibility. Moreover, the perception of prevention and aftercare as optional rather than integral parts of the rehabilitation process diminishes their acceptance and long-term effectiveness.

These findings point to systemic deficits across prevention, rehabilitation, and aftercare. Adherence over time is often low, the transfer of learned behaviors into daily life remains limited, and coordination between insurers, providers, and workplaces is fragmented. To address these gaps, more flexible and patient-centered approaches are required. Digital interventions, in particular, offer promising opportunities by reducing barriers of time and place, supporting adherence through personalized feedback, and potentially enhancing the sustainability of health and work ability outcomes.

# Digital Forms of Prevention, Rehabilitation, and Aftercare

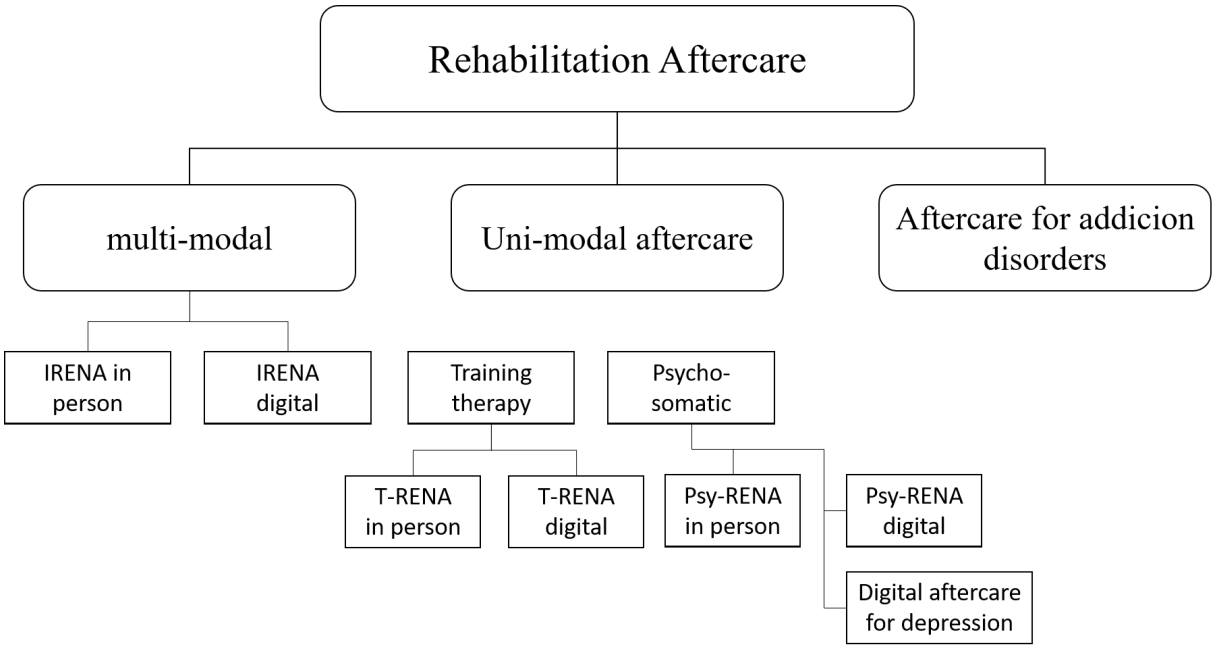
The increasing digitalization of health care has opened new opportunities for prevention, rehabilitation, and aftercare in the German Pension Insurance system. Digital formats respond directly to long-standing challenges in conventional services, such as limited accessibility, low adherence, and regional disparities in provision. By offering flexible, scalable, and often location-independent solutions, they can reach insured persons who would otherwise face barriers to participation, for example due to time constraints, family obligations, or long travel distances. The relevance of digital approaches has been further reinforced by the COVID-19 pandemic, which accelerated the adoption of remote care and demonstrated the feasibility of telehealth models (DRV, 2023a). Against the backdrop of demographic change and rising demands on the workforce, digital interventions are increasingly seen as a strategic complement to traditional programs, with the potential to enhance sustainability, improve adherence, and ensure long-term maintenance of work ability.

Digital prevention programs within the German Pension Insurance system are designed to support insured persons in strengthening their health resources and reducing risk factors before manifest illness or functional limitations occur. These programs typically use web-based platforms, mobile applications, or blended formats that combine online modules with in-person components. Core elements include guidance on physical activity, nutrition, stress management, and lifestyle modification, which can be accessed flexibly and integrated into everyday life. In the occupational context, digital prevention measures are increasingly offered in cooperation with employers and occupational health services, enabling employees to participate without leaving their work environment. By providing modular, user-friendly, and low-threshold access, digital prevention formats expand the reach of the DRV's prevention mandate and complement traditional face-to-face courses such as RV Fit.

Digital rehabilitation services encompass a variety of formats that extend or complement conventional inpatient and outpatient rehabilitation. They make use of telemedicine platforms, video consultations, mobile health applications, and remote monitoring tools to deliver therapeutic content beyond the confines of rehabilitation facilities. Such services can include exercise programs guided by digital applications, online group sessions, or individualized coaching delivered via telecommunication. Hybrid models that combine in-person therapy with digital components are also increasingly applied, allowing for a more continuous rehabilitation process across different settings. Through these approaches, digital rehabilitation enables ongoing medical and therapeutic supervision while offering insured persons greater flexibility in integrating rehabilitation into their everyday lives and work routines.

Digital aftercare, often referred to as Tele-Reha-Nachsorge, has been introduced by the German Pension Insurance as a response to the persistently low uptake of conventional aftercare programs (DRV, 2023a). It provides rehabilitants with the opportunity to continue structured therapeutic activities at home through digital platforms, thereby reducing barriers related to travel, scheduling, and regional availability. Typical components include exercise modules guided by video or app-based instructions, interactive group sessions conducted online, and digital tools for stress management and lifestyle counseling. Programs are usually coordinated by rehabilitation facilities to ensure continuity of care and medical oversight. By embedding therapeutic activities into everyday routines and offering location- and time-independent participation, digital aftercare seeks to sustain the gains achieved during rehabilitation and support the long-term preservation of work ability. The different forms of the digital rehabilitation after are presented in the Figure 2.

Figure 2: Rehabilitation aftercare and its digital equivalents according to DRV (2023b, p. 22).




The expansion of digital formats in prevention, rehabilitation, and aftercare is highly relevant for the present dissertation. As conventional programs continue to face barriers such as limited accessibility, low adherence, and uneven participation, digital interventions offer an alternative that may address these systemic shortcomings. By providing flexible, scalable, and user-centered solutions, they align with the broader objective of the German Pension Insurance to maintain and restore work ability in the context of demographic change and increasing demands on the workforce. This dissertation directly engages with these developments by comparing digital and conventional interventions with regard to their impact on physical and mental health outcomes, work ability, and sustainability of effects. In doing so, it aims to contribute to the scientific understanding of the potential and limitations of digital health interventions, while also providing practical insights for the further development of the German rehabilitation and prevention system.

## Theoretical Background

The theoretical background of this dissertation provides the conceptual framework for analyzing the effectiveness of preventive and rehabilitative interventions in the context of the German Pension Insurance. Since the primary goal of these interventions is the preservation and restoration of employability, it is essential to ground the analysis in established models of health and work ability. Both constructs are central to understanding how prevention, rehabilitation, and aftercare contribute to long-term participation in working life, particularly under the demographic pressures of an aging workforce and increasing prevalence of chronic conditions. Against this backdrop, the following section introduces the theoretical foundations that guide the operationalization of central constructs in this dissertation.

# Conceptualization of Health

## Classical Biomedical Perspective

In its classical biomedical understanding, health is conceptualized primarily as the absence of disease or infirmity (Boorse, 1977). This perspective is rooted in a reductionist medical model that focuses on the diagnosis and treatment of pathological conditions, with the overarching aim of restoring normal bodily functions. Within this framework, health is seen as a largely static state that can be objectively assessed through medical examinations and clinical indicators. While the biomedical perspective has provided the foundation for modern medicine and remains indispensable in acute care and disease management, it is limited in its ability to capture the multidimensional nature of health (Schlitz, 2008). Particularly in the context of prevention and rehabilitation, where the focus lies on maintaining functional capacity and promoting long-term participation in work and society, the biomedical model proves insufficient, as it neglects psychological, social, and contextual factors that shape individual health trajectories.

## WHO Definition and Salutogentic Perspective

A broader understanding of health was introduced with the World Health Organization's definition of 1946, which conceptualizes health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO, 1948, p. 100). This definition marked a paradigmatic shift away from the narrow biomedical view by emphasizing the multidimensionality of health and its positive attributes. It highlights that health is not only the avoidance of illness but also the presence of physical vitality, psychological resilience, and social participation. Although sometimes criticized as utopian for its reference to a state of "complete" well-being, the WHO definition laid the groundwork for modern approaches to health promotion and rehabilitation (Armitage, 2023).

Building on this shift, Antonovsky's salutogenic model further transformed the conceptualization of health by focusing on the origins of health rather than the causes of disease (Antonovsky, 1996). Central to this model is the notion of the sense of coherence, which describes an individual's ability to perceive life as comprehensible, manageable, and meaningful. According to this perspective, health is not a dichotomous state but a dynamic continuum, shaped by the interaction of stressors, coping strategies, and available resources. In the context of prevention and rehabilitation, the salutogenic approach underscores the importance of strengthening individuals' internal and external resources, thereby enabling them to maintain or restore health even in the presence of chronic conditions or functional limitations (Lillefjell et al., 2017). For the German Pension Insurance, this perspective is particularly relevant, as it aligns with the goal of promoting long-term work ability by fostering resilience and resource orientation among insured persons.

## Biopsychosocial Model

The biopsychosocial model, introduced by Engel (1977), represents a further expansion of health concepts by integrating biological, psychological, and social dimensions into a unified framework. In contrast to the reductionist biomedical model, this approach acknowledges that health and illness are determined not only by physiological processes but also by individual behaviors, emotional states, and social contexts. It emphasizes that biological impairments, psychological coping mechanisms, and environmental factors interact dynamically and jointly shape health outcomes.

This model has had a profound influence on modern rehabilitation medicine, where multimodal interventions are designed to address physical symptoms, psychological well-being, and social participation simultaneously (Adler, 2009). In the German rehabilitation system, the biopsychosocial perspective is institutionalized in program design, with multidisciplinary teams providing medical treatment, exercise therapy, psychological counseling, and occupational support. By considering the interaction of different determinants of health, the model enables a more comprehensive understanding of patients' needs and lays the foundation for interventions aimed not only at restoring bodily functions but also at maintaining participation in work and social life.

## Functionalist Concept of Health

Within the theoretical traditions of sociology, Parsons (1951) developed one of the most influential frameworks for understanding health and illness, particularly in relation to their roles within broader social systems. In contrast to biomedical models that primarily focus on individual functional capacity or labor market participation, Parsons' functionalist approach emphasizes the role of health in maintaining societal equilibrium. According to this view, health is not simply a personal condition but a prerequisite for fulfilling socially assigned roles in work, family, and public life. Illness, by contrast, constitutes a form of sanctioned deviance that temporarily relieves individuals of their role obligations while imposing new responsibilities to seek treatment and return to functionality.

Central to Parsons' model is the concept of the "sick role", which outlines a socially regulated set of rights and duties for individuals experiencing illness (Parsons, 1951). The sick person is exempted from normal obligations but is simultaneously expected to desire recovery and to engage with professional healthcare to achieve it. This ensures that illness does not threaten systemic stability by normalizing a temporary withdrawal while promoting reintegration (Nettleton, 2020). In institutional terms, health interventions, especially rehabilitation and prevention, are not solely aimed at restoring individual health but also at reintegrating individuals into the fabric of society.

This sociological understanding is particularly relevant for the German Pension Insurance system, whose statutory mandate includes maintaining employability and delaying disability-related retirement. In this context, rehabilitation and prevention services fulfill not only medical and economic functions but also essential social roles. They act as institutional mechanisms to facilitate the transition from the sick role back to full participation in working life, thereby reinforcing the continuity of social order and economic productivity.

## Implications for This Dissertation

The review of different health concepts demonstrates the need for a multidimensional framework when evaluating interventions in prevention and rehabilitation. While the biomedical perspective remains indispensable for diagnosing and treating medical conditions, it does not capture the psychological, social, and occupational dimensions that are essential for long-term participation in working life. The WHO definition, the salutogenic model, and the biopsychosocial perspective extend this view by emphasizing resources, coping, and the interplay of health determinants.

For this dissertation, these theoretical perspectives provide the foundation for operationalizing health outcomes. The focus extends beyond physical recovery to include psychological well-being, social participation, and especially work ability as an integrative outcome measure. This multidimensional understanding guides the comparison of digital and conventional interventions, ensuring that their evaluation encompasses not only short-term medical effects but also their capacity to sustain health resources and support occupational reintegration. By grounding the research in a comprehensive health concept, the dissertation contributes to a more holistic assessment of intervention effectiveness and aligns closely with the strategic mission of the German Pension Insurance to maintain health and work ability across the life course.

# Conceptualization of Work Ability

## Historical Development of the Concept

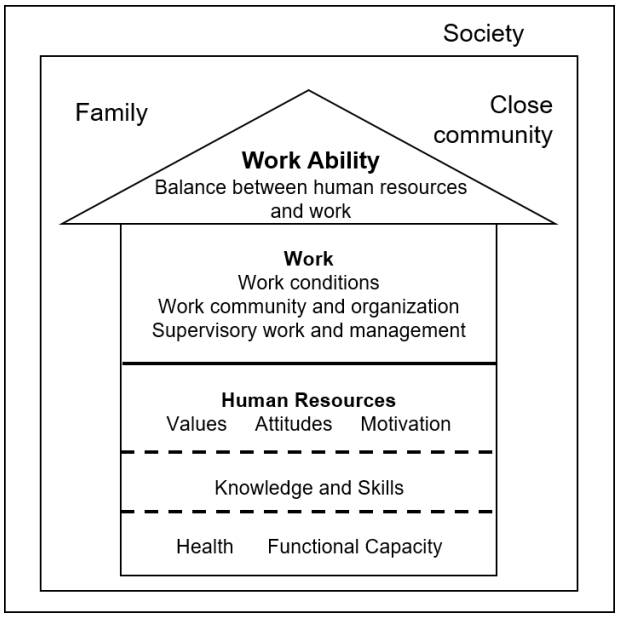
The concept of work ability emerged in the 1980s within the field of occupational health research in Finland, largely shaped by the work of Ilmarinen et al. (1991) at the Finnish Institute of Occupational Health. Their research was motivated by the demographic challenge of an aging workforce and the need to extend working lives in the context of increasing life expectancy and changing labor market demands. Instead of focusing exclusively on disease, impairment, or early exit from the labor force, the concept of work ability emphasized the capacity of individuals to meet the demands of their work across the entire span of their working lives (Ilmarinen, 1999).

This shift represented a paradigmatic change in occupational health thinking. Work ability was no longer seen as a static condition defined by the absence of illness but as a dynamic balance between individual resources, health status, skills, and the requirements of the workplace (Tengland, 2011). This perspective acknowledged that even individuals with chronic conditions could maintain a high level of work ability if sufficient personal, organizational, and societal resources were available. By reframing the discussion from limitations to capacities, the concept of work ability established itself as a central tool for understanding and promoting sustainable employability in aging societies.

## The Work Ability House Model

To capture the multidimensional nature of work ability, Ilmarinen and colleagues developed the Work Ability House model, which has become the most widely applied conceptual framework in occupational health research (Gould et al., 2008). The model presents work ability as a house built on four interrelated levels that together determine the stability of the structure. The foundation consists of health and functional capacities, which include physical fitness, psychological resilience, and the absence of serious illness. The second level refers to professional competence, encompassing education, qualifications, and the capacity to adapt to changing occupational demands. The third level represents values, attitudes, and motivation, which influence the meaning that individuals attribute to their work and the degree of alignment between personal aspirations and professional roles. The top level reflects work-related factors such as job demands, work environment, leadership, and organizational structures (Gould et al., 2008).

Figure 3: House of Work Ability according to Gould et al. (2008, p. 19).




The house metaphor highlights that work ability is a dynamic construct shaped by the balance of these levels. A decline in one domain, for example reduced health, loss of motivation, or adverse working conditions, can undermine the

stability of the entire structure. Conversely, strengthening one level can compensate for weaknesses in another (Gould et al., 2008), thereby preserving work ability even under challenging circumstances. This perspective underscores the importance of interventions that address health, skills, motivation, and organizational conditions simultaneously. As a result, the Work Ability House has become a guiding framework for prevention and rehabilitation strategies (Martinez et al., 2016), particularly in societies facing demographic change and the need to extend working lives.

# The Work Ability in the German Pension Insurance Context

Within the German Pension Insurance system, the concept of work ability occupies a central position. The mandate of the institution is not only to provide financial security in cases of disability or reduced earning capacity but also, and increasingly, to maintain and restore work ability through preventive and rehabilitative measures. This orientation reflects the recognition that sustainable participation in working life is essential both for the individual and for the stability of the social insurance system in the context of demographic change.

Rehabilitation services funded by the German Pension Insurance are explicitly designed to secure or restore the capacity of insured persons to remain active in the labor market. The focus extends beyond medical treatment to encompass the broader dimensions of employability as described in the Work Ability House model. Preventive programs such as RV Fit aim to strengthen individual resources before manifest illness occurs, while rehabilitation programs address existing health impairments and their functional consequences (DRV, 2020). Aftercare services, including both conventional and digital formats, are intended to stabilize gains achieved during rehabilitation and to support the transfer of learned strategies into everyday working life (Sewöster, 2023).

The legal framework under the Social Code, in particular Book VI (SGB VI), anchors work ability as a guiding principle of the German rehabilitation system. Maintaining employability is explicitly formulated as the primary goal of pension insurance rehabilitation, distinguishing it from health insurance, which primarily aims at restoring health. This orientation ensures that measures financed by the German Pension Insurance are systematically linked to occupational outcomes. Consequently, the preservation of work ability functions as both a normative foundation and a practical evaluation criterion for prevention and rehabilitation within the German context.

# Implications for This Dissertation

The conceptualization of work ability provides an essential theoretical foundation for this dissertation. As shown in the historical development and in the Work Ability House model, work ability is not a static condition but the result of a dynamic interaction between health, professional competence, motivation, and work-related factors. This multidimensional view is particularly relevant in the context of prevention and rehabilitation, where the aim is not only to address medical conditions but also to strengthen resources that enable long-term participation in working life.

For the German Pension Insurance, work ability is both a normative principle and a central evaluation criterion. Its focus on maintaining employability differentiates it from other branches of social insurance and underlines the importance of integrating occupational outcomes into health interventions. This orientation justifies the use of work ability as a primary outcome in this dissertation, complementing more traditional measures of physical and mental health.

In the empirical studies included in this dissertation, work ability serves as the key indicator for assessing the effectiveness of digital and conventional interventions. By examining not only short-term health effects but also the sustainability of work participation, the dissertation aligns with the mission of the German Pension Insurance to maintain employability in the face of demographic change. Furthermore, by investigating moderating factors such as age, gender, and employment status, the dissertation contributes to a more differentiated understanding of how interventions influence work ability in diverse population groups.

# Research Questions of the Dissertation

## Overarching Research Aim

This dissertation aims to empirically investigate the effectiveness of digital compared to conventional formats in the context of prevention and rehabilitation aftercare, with a particular emphasis on work ability, physical health, and mental health. The studies are situated within the institutional framework of the German Pension Insurance, whose strategic mission is to preserve and restore employability. The research program consists of three analyses basing on two independent quasi-experimental studies, each addressing a specific segment of the prevention and rehabilitation continuum.

## Study-Specific Research Questions and Hypotheses

### Study I: Digital vs. Conventional Prevention

Research Question I

To what extent do digital prevention programs improve physical and mental health and work ability compared to conventional programs among employees with initial health impairments?

### Study II: Digital vs. Conventional Aftercare – Health Outcomes

Research Question II

How do digital (digIRENA) and conventional (IRENA) rehabilitation aftercare programs compare in terms of sustaining improvements in physical and mental health over time in orthopedic patients?

### Study III: Digital vs. Conventional Aftercare – Work Ability

Research Question III

Does digital rehabilitation aftercare (digIRENA) result in greater improvements in work ability compared to conventional IRENA or no organized aftercare in orthopedic patients?

To address these research questions, the dissertation integrates three empirical studies that systematically examine the comparative effectiveness of digital and conventional interventions within the German rehabilitation and prevention system. These three studies will be presented in the following chapters.

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# Chapter II – The effectiveness of a digital prevention

Study 1: Impact of a Digital and Conventional Prevention Program on Work Ability, Physical Health, and Mental Health among Employees with Initial Impairments

Slightly modified version of the published manuscript:

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## Abstract

**Background**: This quasi-experimental study aimed to compare the effectiveness of a digital prevention intervention on work ability, physical health, and mental health with a conventional prevention program for employees with initial impairments. The study recruited 245 participants, of whom 173 completed the study, 98 (65 female, 66.3%) in the intervention group and 75 (55 female, 73.3%) in the control group. Both groups received prevention programs, with the intervention group using the Caspar digital platform and the control group using the conventional BETSI/RV Fit program. There were three measurement points in the study: T0 before the intervention, T1 in the middle of the intervention, and T2 at the end of the intervention. Participants' health was assessed using the SF-12 health status questionnaire, while their work ability was measured using the short version of the Work Ability Index.

**Results**: Repeated-measures analyses of variance indicated that both prevention programs were effective in improving work ability and mental health, while physical health did not show any significant improvement. Additionally, the results of the study suggest that younger individuals benefited more from the digital prevention intervention, while older individuals benefited more from the conventional prevention program.

**Conclusion**: The study emphasizes the need for further research and improvements in both research and practice. Future studies should include larger sample sizes, randomized controlled trials, and follow-up assessments to enhance understanding of the effectiveness and the durability of effects of prevention programs.

## Background

One of the greatest challenges facing Western societies is demographic change, reflected in a declining number of younger people and a growing number of older people. For example, in Germany in 2021, for every 100 people of working age between 20 and 65, there were around 37 people of pensionable age, i.e. over 65 (Bundesamt, 2021). This trend will intensify in the coming years as the baby boomers reach retirement age, posing a major challenge for the country's social systems. Therefore, a well-functioning health care system plays a crucial role in maintaining the workforce's ability to work at a high level.

Prevention is a critical aspect of maintaining and promoting overall health and well-being, as evidenced by numerous public health studies. For instance, a systematic review and meta-analysis of 78 studies found that lifestyle interventions, including health behaviors such as healthy diet and exercise, were effective in reducing the incidence of type 2 diabetes (Schellenberg et al., 2013). Similarly, a study on the impact of preventive care in the United States found that preventive services were associated with improved health outcomes and reduced health care costs (Maciosek et al., 2006). In addition to physical health, prevention also plays a significant role in promoting mental health (WHO, 2002). Research has demonstrated the effectiveness of stress reduction techniques and therapy in preventing and treating mental health conditions such as depression and anxiety (Rith-Najarian et al., 2019). By taking proactive measures to prevent disease and injury, individuals and the society as a whole can reap numerous benefits, including improved health outcomes (Patel & Patel, 2019), reduced healthcare costs (Loeppke, 2008), and enhanced quality of life (Pomaki et al., 2012; Santos et al., 2011).

With the aim of promoting healthy living and working strategies among the workforce in Germany at an early stage, the German Pension Insurance launched the nationwide prevention program BETSI (Beschäftigungsfähigkeit teilhabeorientiert sichern) in 2013 and renamed it RV Fit in 2020. The theoretical approach behind RV-Fit is based on a bio-psycho-social model that takes into account the physical, psychological, and social aspects of health (Lehman et al., 2017). This model aligns with the World Health Organization's International Classification of Functioning, Disability, and Health (ICF) (Üstün et al., 2003). The ICF views health and disability as a continuum and recognizes that both personal and environmental factors can influence an individual's functioning. The RV-Fit approach attempts to consider the complex interaction of these factors by providing individualized assessment and intervention to meet the specific needs of each person.

BETSI/RV Fit works with employers to develop and implement effective reintegration plans for employees who are experiencing initial health impairments that impact their ability to work. These initial health impairments may be characterized by the following possible features: a) pain complaints in the musculoskeletal system (e.g., back pain), b) health impairments related to internal organs (e.g., high blood pressure, obesity), c) psychological impairments (e.g., occupational overwhelm, stress), d) individual risk factors such as smoking, poor dietary habits, or lack of physical activity, and e) unfavorable working conditions (e.g., stress due to shift work, workload density, performance pressure, noise, cold, heat, monotonous standing or sitting posture, etc.).

The program advises and supports employers on issues such as workplace adaptations, job accommodations, and modified work schedules for employees. BETSI/RV Fit also works closely with healthcare providers to ensure that employees receive the necessary medical care and rehabilitation services (see also Methods section). There is some evidence that the BETSI/RV Fit program has been successful in supporting the reintegration of employees with health issues back into the workplace. According to a prospective study by Kittel et al. (Kittel et al., 2014), participation in BETSI/RV Fit was found to be associated with significant reductions in risk factors such as physical inactivity, stress, and obesity, leading to better health outcomes and a positive subjective prognosis of work ability. Despite the evidence of the effectiveness of BETSI/RV Fit, however, there are challenges related to access and implementation. For example, access to appropriate facilities offering BETSI/RV Fit can be difficult, especially in rural areas.

Digital health promotion and prevention programs have gained increasing popularity in recent years due to their potential to address public health concerns on a larger scale, to reduce healthcare costs, and to provide access to evidence-based interventions to individuals who may otherwise have no access to traditional prevention programs (Stark et al., 2022). Digital health promotion and prevention programs use digital technologies such as mobile applications, websites, and social media platforms to deliver health education, monitoring, and intervention programs aimed at promoting healthy behaviors and preventing chronic diseases (Arigo et al., 2019). Several studies have suggested the potential of digital prevention programs in promoting healthy behaviors, preventing chronic disease and assisting with weight loss (Beleigoli et al., 2019). For instance, a study with a randomized wait-list controlled trial design found that a self-administered web-based intervention that targeted physical activity and healthy eating behaviors resulted in significant reductions in body mass index, body fat mass, and blood glucose (Lisón et al., 2020). In addition, a systematic review of 41 studies showed that several mobile phone applications were effective in increasing health behaviors such as physical activity (Hosseinpour & Terlutter, 2019).

Despite the demonstrated benefits and potential of digital prevention programs to promote healthy behaviors and prevent chronic diseases on a larger scale, there are few studies in Germany that address the effectiveness of digital prevention programs. Little is known about the effectiveness of digital prevention programs compared to traditional prevention programs such as BETSI/RV Fit. To address these research gaps, this study aimed to examine the effectiveness of a digital prevention intervention on work ability, physical health, and mental health of employees who are experiencing initial impairments. The effectiveness of the intervention was tested in comparison with the conventional prevention program BETSI/RV Fit. The study also aimed to examine the influence of age and gender on the effectiveness of the interventions. In addition, we wanted to investigate to what extent age exerts an influence on the effectiveness of digital and conventional prevention.

# Methods

## Design of the Study

This study was registered at the German Register of Clinical Studies (DRKS) with the registration number: DRKS00024836. This study had a quasi-experimental design with two groups and three measurement time points. Participants in the experimental group were recruited from a clinic that offered the digital prevention program to its patients. In order to compare this treatment with the conventional prevention program, it was necessary to recruit participants from other clinics offering only the conventional program. Therefore, it was not possible to randomize the study participants. In addition, it is important to mention the researcher were not blinded to the assignment, however, they did not have any direct contact with the participants throughout the entire intervention. The intervention group received a digital prevention program, and the control group received the conventional prevention program BETSI/RV Fit. The first measurement time point (T0) took place immediately before the prevention intervention, the second measurement time point (T1) in the middle of the prevention intervention (12 weeks after the start of the intervention) and the third measurement time point (T2) at the end of the intervention (24 weeks after the start of the intervention). The study started with an inpatient or outpatient stay for the control group for three to five days and an inpatient stay for the intervention group lasting 14 days. Participants in the intervention group stayed at the Knappschafts-Klinik Borkum, where the digital prevention program was used, and participants in the control group stayed at one of the participating prevention clinics or health centers offering BETSI/RV Fit (i.e., Ambulantes Zentrum für Rehabilitation und Prävention am Entenfang in Karlsruhe, Fachklinik Sonnenhof GmbH in Höchenschwand, and Prevention Center Darmstadt). Participants in the two groups were recruited at the respective clinics or health centers.

The baseline measurement (T0) was conducted during the clinic stay, during which participants received the questionnaires, an informed consent form, and a contact sheet. Participants returned these documents to the study management, which ensured strict compliance with the data protection guidelines of the Karlsruhe Institute of Technology. At the second and third measurement time points (T1 and T2), the participants were provided with the necessary documents directly by the study management, either by e-mail or mail, as requested by the participants. The same procedure was used for both groups. The study was conducted in accordance with the tenets of the Helsinki Declaration and approved by the Data Protection Officer and the Ethics Committee of the Karlsruhe Institute of Technology (328-18 1200).

## Sample

Participants for the study were recruited from December 2019 to October 2022 through the Knappschafts-Klinik Borkum for the intervention group and various health centers and specialist clinics for the control group. Potential participants were identified by healthcare professionals who assessed eligibility based on specific criteria, including being an employee covered by pension insurance and experiencing initial signs of impairment such as musculoskeletal pain, internal organ ailments, or individual risk factors like smoking or poor nutrition. Individuals were also required to enroll independently in the designated prevention course. Based on the assumption of a small effect size ($f = 0.10$), an alpha error rate of 0.05, two groups, three measurement time points, a correlation of 0.50 among repeated measures, and utilizing an ANOVA with repeated measures for evaluation, the required sample size was $N = 164$ in order to achieve a statistical power of 0.80. Recognizing that some subjects may drop out during the longitudinal study, the goal was to recruit 240 subjects at the first measurement point. The study recruited a total of 245 subjects for the first measurement time point, prior to the implementation of the intervention. Of these, 147 subjects (88 female; 59.9%) were in the intervention group, and 98 subjects (69 female; 70.4%) were in the control group. Participants who missed at least six consecutive weeks of sessions were excluded from the study, and additionally, eight participants who reported no participation in conventional or digital prevention at any of the measurement time points were also excluded. Data from 173 subjects who completed questionnaires at all three measurement time points were analyzed. Among these 173 study participants, 98 (65 female; 66.3%) were in the intervention group, and 75 (55 female; 73.3%) were in the control group. The mean age of the intervention group at the start of the inpatient prevention intervention was 51.5 years ($SD = 7.8$), while the mean age of the control group participants at the initial inpatient phase was 51.9 years ($SD = 7.8$). Regarding employment status, 78 individuals in the intervention group were employed full-time and 20 (20.4%) were employed part-time. In the control group, 51 individuals were employed full-time and 24 (32.4%) were employed part-time.

## Measures

Two validated questionnaires were used to assess health and work ability. Work ability was measured using the Work Ability Index (WAI) (Hasselhorn & Freude, 2007) and health using the SF-12 (Morfeld et al., 2011). The questionnaires are described below.

### Health

Health was measured by the licensed SF-12 health status questionnaire, whose license was obtained for the purpose of the study. This is the short version of the SF-36 (Morfeld et al., 2011). The SF-12 includes the two subscales physical health and mental health. This questionnaire, which can be applied independently of the current state of health, was shown to be a suitable measurement instrument for assessing subjective health (Morfeld et al., 2011). The response format contains different multilevel Likert scales as well as dichotomous scales. In terms of reliability, study results showed an internal consistency (Cronbach's α) of .83 for physical health and .87 for mental health (Morfeld et al., 2011). Regarding the validity of the questionnaire, the question wording was rated as comprehensible and relevant across samples (Bullinger & Kirchberger, 1998). There is a representative database for the SF-12 and, therefore, the data can be compared with a norm group (Radoschewski & Bellach, 1999).

### Work Ability

The freely available short version of the Work Ability Index by Hasselhorn and Freude (Hasselhorn & Freude, 2007) was used to assess work ability (www.wainetzwerk.de). The questionnaire consists of 10 items with categorical and continuous response formats. Seven dimensions are mapped: I. current work ability compared to the best ever work ability, II. current work ability to current work demands, III. number of diseases currently diagnosed by a physician, IV. estimated impairment of work ability due to diseases, V. sick leave days in the past 12 months, VI. assessment of own ability to work in the last two years, and VII. mental performance reserve. The total score of the scale varies between 7 and 49 with higher values reflecting higher work ability. The reliability of the scale is Cronbach's alpha of 0.78 (Martus et al., 2011). The validity of the scale has been demonstrated by its ability to predict early career exit and duration of work disability (Burdorf et al., 2005; Salonen et al., 2003).

## Intervention

This research involved the implementation of two intervention programs, namely the conventional face-to-face prevention program (BETSI/RV Fit) and the digital intervention program. These interventions were administered by a qualified physiotherapist who determined the contents of the program. In the digital program, patients who did not regularly use the app were encouraged by the intervention provider to remain engaged. Throughout the interventions, patients in both programs were under the continuous supervision of certified therapists. In the event of potential adverse effects resulting from the prevention, patients could be referred to appropriate treatment.

### Intervention Group

The Knappschafts-Klinik Borkum has developed a prevention concept that incorporates a digital program. For participants, the program involved a 14-day inpatient stay in Borkum. Upon arrival on Borkum, participants underwent a comprehensive assessment to identify their specific needs, challenges and goals. This phase included one-on-one interviews, health screenings and baseline measurements to tailor the subsequent program to the individual’s needs. After the initial assessment, participants entered the phase that formed the core of the intervention. This phase included an intensive, structured series of exercises, therapies, and educational sessions targeting the physical, mental, and social aspects of health. In this phase, the focus was on skill development, empowerment, and self-management strategies so that participants were equipped with the tools and knowledge they need to maintain and improve their health and ability to work. During the inpatient stay, each patient received an individual training plan, which was practiced with Caspar and served as the basis for the subsequent aftercare with the Caspar digital platform. At the end of the inpatient stay, participants practiced returning to their daily lives and using the digital application. This final phase of the program reinforced the skills and knowledge acquired and ensured that participants can confidently apply what they have learned. Interactive workshops, follow-up assessments and personalized feedback helped participants integrate the principles of the program into their daily routines and work environment. After this, the participants were provided with six months of aftercare via the Caspar digital platform (https://caspar-health.com/en-us). For this six months of follow-

up support, the digital platform Caspar included an individualized training plan designed by the clinic for each participant, supplemented by additional content such as modules on nutrition and relaxation techniques. The application's functionality extended to allow interactive communication between participants and therapists via integrated interfaces within the Caspar platform. This feature facilitated ongoing collaboration and served as a vital connection linking participants with therapeutic professionals, thus augmenting the continuity and cohesiveness of the intervention.

### Control Group

BETSI/RV Fit was a multi-phase intervention with different variations in its implementation and typically comprised four phases. The initial phase of the intervention spanned a few days and could be conducted on an inpatient or outpatient basis. This phase included comprehensive medical supervision, including the availability of therapeutic and medical experts for consultation purposes to accurately assess individual health needs. As in the digital prevention, personalized prevention goals were established during one-on-one consultations with healthcare professionals. Various training sessions were also held to promote positive health behaviors. Participants could engage in workshops or seminars, covering essential topics such as increased physical activity, healthy eating habits, and effective stress management techniques. The interaction with healthcare professionals during this phase ensured that participants' unique health requirements were carefully identified and appropriately addressed. The training phase of the program lasted up to three months, during which participants attend weekly outpatient courses tailored to help them achieve their specific prevention goals. These courses can include fitness classes, nutritional counseling, or behavioral therapy, aiming to form long-term habits. The self-initiative phase spanned approximately three months and placed an emphasis on personal initiative and responsibility. During this period, participants worked independently to adapt the behaviors they have had learned, using resources and strategies provided earlier during the training phase. They may have engaged in regular check-ins with healthcare providers who monitored their progress, offered guidance, and provided support as needed. The refresher phase, serving as the final part of the program, convened participants in a group setting for a day or more to evaluate the overall effectiveness of the entire prevention program. This phase provided an opportunity to review and reaffirm goals, and discuss both challenges and successes. Beyond mere reflection, the refresher phase also served as a platform for future planning, allowing participants to set new goals and ensuring they have continued support and motivation for maintaining a healthy lifestyle.

## Statistical Analyses

The data analysis involved three sequential steps. The first step involved computing means, frequency distributions, standard deviations, and correlations between the recorded variables using descriptive statistics. A t-test was conducted to determine significant differences between the two groups at time T0 for the continuous variables, while a chi-square test was utilized to examine gender differences. The second step involved conducting repeated-measures analyses of variances to investigate the effects of the two interventions and compare their outcomes. Within-subject contrasts with linear and quadratic trends were reported in the context of ANOVA analyses, with work ability, mental health, and physical health being dependent variables and time and group membership being independent variables. In the third step, the same analysis of variance was conducted, incorporating age and gender as covariates. We expected a three-way interaction among time, age, and group for the mental health variable. To achieve this, the age variable was dichotomized at 47, with individuals older than 47 years classified as older participants and those exactly 47 years old and younger as younger participants. In addition, we also checked for the influence of the employment status, but it did not affect the results and we have not presented the results in this manuscript. All analyses were performed with a significance level of 5%. In the correlation matrix (Table 2), p-values were adjusted for multiple testing using the Bonferroni-Holm correction method. Participants excluded from the study due to dropout were statistically comparable to the 173 participants included in the analysis in terms of variables used in the study. Little's MCAR test was performed with variables at all three measurement time points and yielded a nonsignificant result ($\chi^2 = 32.6$; $df = 46$; $p = 0.93$), indicating that the missing data did not exhibit a systematic pattern.

# Results

## Descriptive Analyses

Table 1 displays the descriptive statistics. The results indicate that there were no statistically significant differences between the two groups regarding work ability ($t = 0.5$; $df = 171$; $p = .61$), physical health ($t = 1.3$; $df = 171$; $p = .20$), mental health ($t = 1.4$; $df = 171$; $p = .17$), age ($t = -0.3$; $df = 171$; $p = .74$), and gender ($\chi^2 = 1.0$; $df = 1$; $p = .32$) prior to the commencement of the intervention.

Table 1: Means and standard deviations for work ability, physical health, and mental health

| | | | Work Ability | | Physical Health | | Mental Health | |
|---|---|---|---|---|---|---|---|---|
| | Group | N | Mean | SD | Mean | SD | Mean | SD |
| T0 | IG | 98 | 34.7 | 6.5 | 47.8 | 8.9 | 45.2 | 11.8 |
| | CG | 75 | 34.2 | 7.1 | 46.2 | 9.6 | 42.8 | 11.4 |
| | Total | 173 | 34.5 | 6.8 | 47.1 | 9.2 | 44.1 | 11.7 |
| T1 | IG | 98 | 36.1 | 6.6 | 46.6 | 9.0 | 48.6 | 10.3 |
| | CG | 75 | 35.7 | 7.4 | 46.7 | 10.9 | 45.8 | 10.9 |
| | Total | 173 | 35.9 | 6.9 | 46.6 | 9.9 | 47.4 | 10.6 |
| T2 | IG | 98 | 35.8 | 7.5 | 47.1 | 9.2 | 48.7 | 10.4 |
| | CG | 75 | 35.0 | 8.5 | 45.3 | 10.6 | 46.9 | 10.6 |
| | Total | 173 | 35.5 | 8.0 | 46.3 | 9.8 | 47.9 | 10.5 |

Note: IG: Intervention Group; CG: Control Group; SD: Standard Deviation.

Table 2 displays the correlation matrix for the variables utilized in the present analyses. The findings suggest a statistically significant positive correlation between age and mental health at T0. Moreover, gender had a significant positive correlation with the work ability and mental health at T0 and T1. The positive correlation of gender indicated that men exhibited higher scores than women across these variables. Age and gender showed no significant correlation.

Table 2: Correlation matrix

| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| Age (1) | .00 | -.14 | -.19 | .21* | -.20 | -.16 | .05 | -.09 | -.11 | .04 |
| Gender (2) | | .21* | .05 | .26* | .23* | .15 | .21* | .17 | .13 | .15 |
| WAI T0 (3) | | | .47* | .54* | .70* | .36* | .43* | .67* | .32* | .49* |
| Phys Health T0 (4) | | | | -.13 | .48* | .67* | .02 | .43* | .44* | .20 |
| Ment Health T0 (5) | | | | | .37* | .01 | .61* | .35* | .09 | .55* |
| WAI T1 (6) | | | | | | .52* | .54* | .80* | .42* | .51* |
| Phys Health T1 (7) | | | | | | | -.06 | .48* | .58* | .20 |
| Ment Health T1 (8) | | | | | | | | .47* | .11 | .64* |
| WAI T2 (9) | | | | | | | | | .58* | .60* |
| Phys Health T2 (10) | | | | | | | | | | .11 |
| Ment Health T2 (11) | | | | | | | | | | |

Note: *: Bonferroni-Holm adjusted for $p < .05$; WAI: Work Ability Index; Phys Health: Physical Health; Ment Health: Mental Health.

## Analyses of Variance

The results of the analysis of variance demonstrated significant time effects on work ability, which comprises both linear ($\eta^2 = .03$) and quadratic ($\eta^2 = .06$) components (see Table 3). In contrast, the interaction between time and group was not significant in neither the linear nor the quadratic trend. Figure 4 depicts the mean trend across the measurement time points for both groups. It is observed that there was a relatively steep increase in WAI for both groups from T0 to T1, followed by a slight decrease in WAI scores from T1 to T2.

Table 3: Analyses of variances for work ability, physical health, and mental health.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Work Ability | | | |
| | Trend | SS | df | MSS | F | P | $\eta^2$ |
| T | Linear | 82.7 | 1 | 82.7 | 4.5 | .04 | .03 |
| | Square | 11.5 | 1 | 11.5 | 1.2 | <.01 | .06 |
| T * Gr | Linear | 1.8 | 1 | 1.8 | 0.1 | .75 | .00 |
| | Square | 3.1 | 1 | 3.1 | 0.3 | .59 | .00 |
| Error | Linear | 3139.7 | 171 | 18.4 | | | |
| | Square | 1849.7 | 171 | 1.8 | | | |
| | | | | Physical Health | | | |
| T | Linear | 46.2 | 1 | 46.2 | 1.0 | .33 | .01 |
| | Square | 0.1 | 1 | .1 | 0.0 | .95 | .00 |
| T * Gr | Linear | 1.4 | 1 | 1.4 | 0.0 | .87 | .00 |
| | Square | 94.2 | 1 | 94.2 | 3.0 | .08 | .02 |
| Error | Linear | 8284.4 | 173 | 47.9 | | | |
| | Square | 5405.2 | 173 | 31.2 | | | |
| | | | | Mental Health | | | |
| T | Linear | 1257.3 | 1 | 1257.3 | 24.1 | <.01 | .12 |
| | Square | 186.4 | 1 | 186.4 | 4.5 | .04 | .03 |
| T * Gr | Linear | 9.5 | 1 | 9.5 | 0.2 | .67 | .00 |
| | Square | 17.1 | 1 | 17.1 | 0.4 | .52 | .00 |
| Error | Linear | 9012.7 | 173 | 52.1 | | | |
| | Square | 7139.6 | 173 | 41.3 | | | |

Note: *: $p < .05$; WAI: Work Ability Index; Phys Health: Physical Health; Psych Health: Mental Health; SS: Sum of Squares; MSS: Mean Sum of Squares; df: degrees of freedom; T: Time; Gr: Group.

Figure 4: Mean value progression over the three measurement points for work ability, physical health, and mental health.

Figure 4: Development of work ability

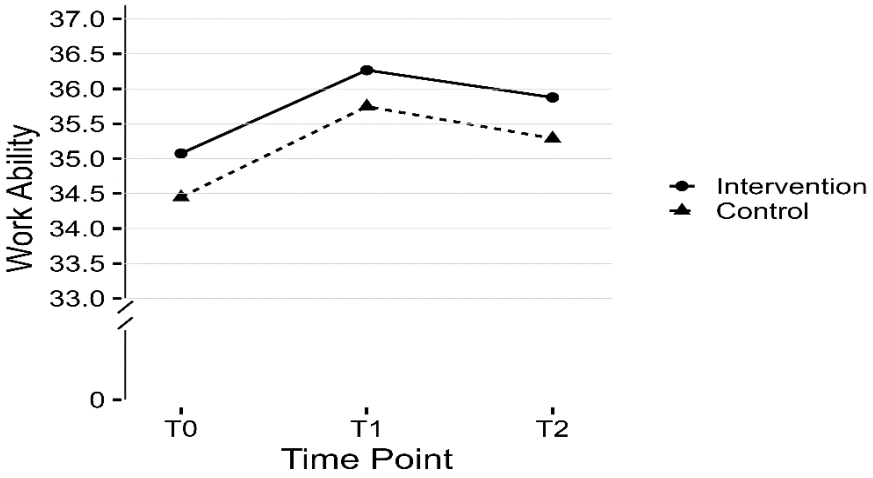



Figure 5: Development of physical health

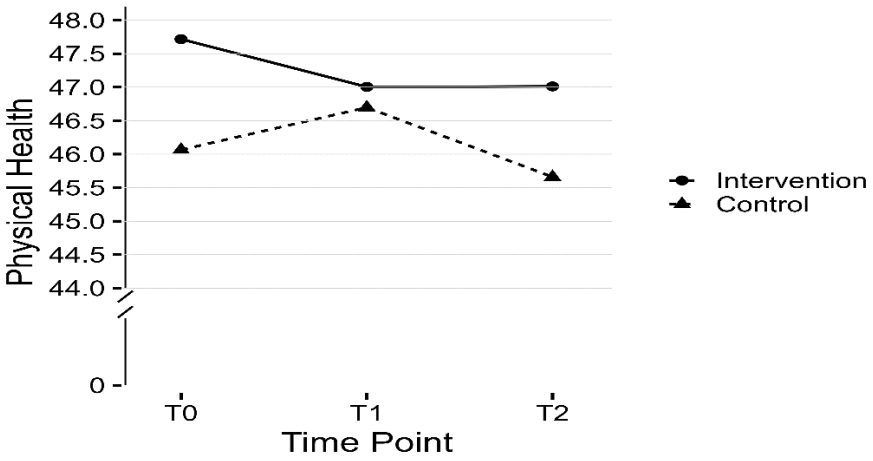
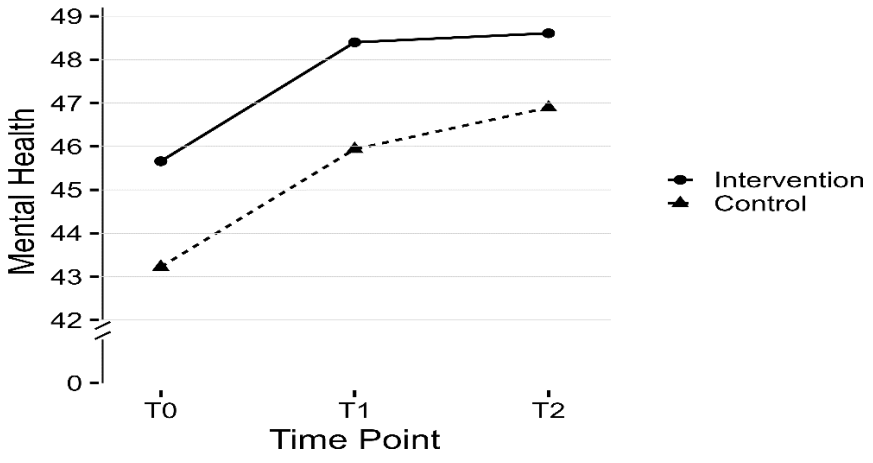



Figure 6: Development of mental health



Regarding physical health, the time effect and the interaction between time and group did not show any linear or quadratic trend. The development of physical health in both groups is shown in Figure 5. Concerning mental health, a significant time effect was observed, comprising both a linear ($\eta^2 = .12$) and a quadratic ($\eta^2 = .03$) trend. Figure 6 demonstrates a very steep increase from T0 to T1 and a somewhat flattened increase from T1 to T2. The interaction effect between time and group did not show any significant linear or quadratic trend.

## Analyses of Variance with Age and Gender

In the statistical analysis of work ability, age was included as a covariate and gender as an additional factor. The results of the analysis of variance showed that none of the independent variables had a significant effect on work ability. In addition, the effect of time on work ability was not significant in neither the linear nor the quadratic trend (see Table 4). For physical health, the same pattern emerged, as no significant effect was observed for any of the independent variables. Conversely, for mental health, a significant effect was observed only for time in the linear trends.

## Interaction between Time, Group, and Age

A repeated-measures analysis of variance was conducted to investigate the three-way interaction among time, group, and age, with age being dichotomized. The results revealed a significant three-way interaction effect for the linear trend in mental health ($F = 5.3$; $df_1 = 1$; $df_2 = 165$; $p < .05$; $\eta^2 = .03$) and the quadratic trend in work ability ($F = 7.5$; $df_1 = 1$; $df_2 = 165$; $p < .05$; $\eta^2 = .04$), but not for physical health ($F = 2.7$; $df_1 = 1$; $df_2 = 167$; $p < .05$; $\eta^2 = .00$). Specifically, younger participants displayed a significant improvement in the intervention group for both work ability (Figure 7) and mental health (Figure 9), whereas older participants demonstrated a greater improvement in the control group for both work ability (Figure 8) and mental health (Figures 10).

Table 4: Analyses of variances for work ability, physical health, and mental health, including age and gender.

| | | Work Ability | | | | | |
|---|---|---|---|---|---|---|---|
| | Trend | SS | df | MSS | F | P | $\eta^2$ |
| Time | Linear | 0.5 | 1 | 0.5 | 0.0 | 0.87 | 0.00 |
| | Square | 31.6 | 1 | 31.6 | 3.0 | 0.09 | 0.02 |
| Time * Age | Linear | 3.8 | 1 | 3.8 | 0.2 | 0.65 | 0.00 |
| | Square | 15.0 | 1 | 15.0 | 1.4 | 0.24 | 0.01 |
| Time * Group | Linear | 3.4 | 1 | 3.4 | 0.2 | 0.67 | 0.00 |
| | Square | 0.6 | 1 | 0.6 | 0.1 | 0.81 | 0.00 |
| Time * Gender | Linear | 3.3 | 1 | 3.3 | 0.2 | 0.68 | 0.00 |
| | Square | 17.6 | 1 | 17.6 | 1.6 | 0.20 | 0.01 |
| T * Gr * Ge | Linear | 1.3 | 1 | 1.3 | 0.1 | 0.79 | 0.00 |
| | Square | 9.3 | 1 | 9.3 | 0.9 | 0.35 | 0.01 |
| Error | Linear | 3132.1 | 168 | 18.6 | | | |
| | Square | 1798.4 | 168 | 10.7 | | | |
| | | Physical Health | | | | | |
| Time | Linear | 23.3 | 1 | 23.3 | 0.5 | 0.49 | 0.00 |
| | Square | 0.5 | 1 | 0.5 | 0.0 | 0.90 | 0.00 |
| Time * Age | Linear | 19.0 | 1 | 19.0 | 0.4 | 0.53 | 0.00 |
| | Square | 1.0 | 1 | 1.0 | 0.0 | 0.86 | 0.00 |
| Time * Group | Linear | 1.3 | 1 | 1.3 | 0.0 | 0.87 | 0.00 |
| | Square | 32.1 | 1 | 32.1 | 1.0 | 0.31 | 0.01 |
| Time * Gender | Linear | 35.5 | 1 | 35.5 | 0.7 | 0.39 | 0.00 |
| | Square | 26.5 | 1 | 26.5 | 0.8 | 0.36 | 0.01 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| T * Gr * Ge | Linear | 9.9 | 1 | 9.9 | 0.2 | 0.65 | 0.00 |
| | Square | 85.2 | 1 | 85.2 | 2.7 | 0.10 | 0.02 |
| Error | Linear | 8181.9 | 168 | 48.7 | | | |
| | Square | 5263.8 | 168 | 31.3 | | | |
| | | Mental Health | | | | | |
| T | Linear | 325.0 | 1 | 325.0 | 6.3 | 0.01 | 0.04 |
| | Square | 97.8 | 1 | 97.8 | 2.3 | 0.13 | 0.01 |
| T * Age | Linear | 183.7 | 1 | 183.7 | 3.5 | 0.06 | 0.02 |
| | Square | 64.7 | 1 | 64.7 | 1.5 | 0.22 | 0.01 |
| T * Gr | Linear | 11.7 | 1 | 11.7 | 0.2 | 0.64 | 0.00 |
| | Square | 14.4 | 1 | 14.4 | 0.3 | 0.56 | 0.00 |
| T * Ge | Linear | 95.2 | 1 | 95.2 | 1.8 | 0.18 | 0.01 |
| | Square | 1.9 | 1 | 1.9 | 0.0 | 0.83 | 0.00 |
| T * Gr * Ge | Linear | 12.2 | 1 | 12.2 | 0.2 | 0.63 | 0.00 |
| | Square | 1.0 | 1 | 1.0 | 0.0 | 0.88 | 0.00 |
| Error | Linear | 8696.5 | 168 | 51.8 | | | |
| | Square | 7060.7 | 168 | 42.0 | | | |

Note: *: p < .05; SS: Sum of Squares; MSS: Mean Sum of Squares; df: degrees of freedom; T: Time; Gr: Group; Ge: Gender.

Figure 7-10: Mean work ability / mental health progression for young and old participants in both groups.

Figure 7: Development in the intervention group in work ability

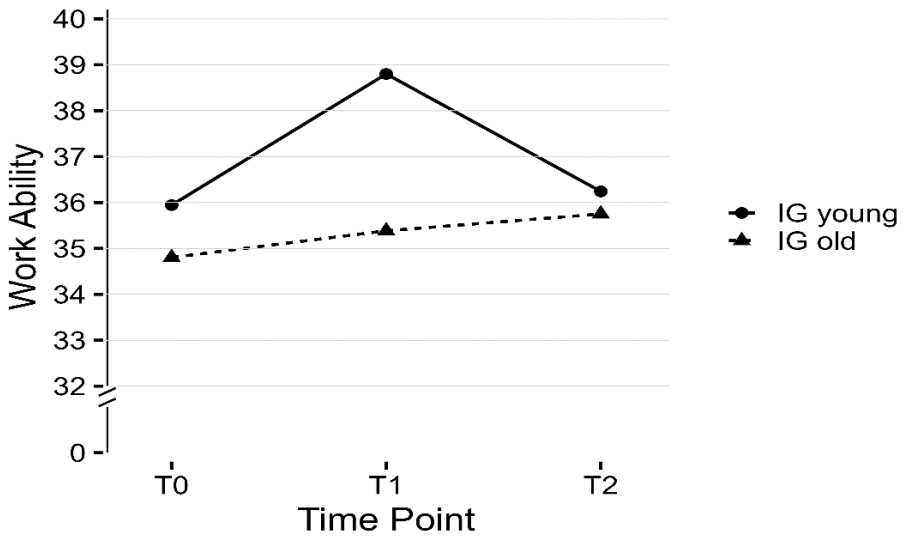


Figure 8: Development in the control group in work ability

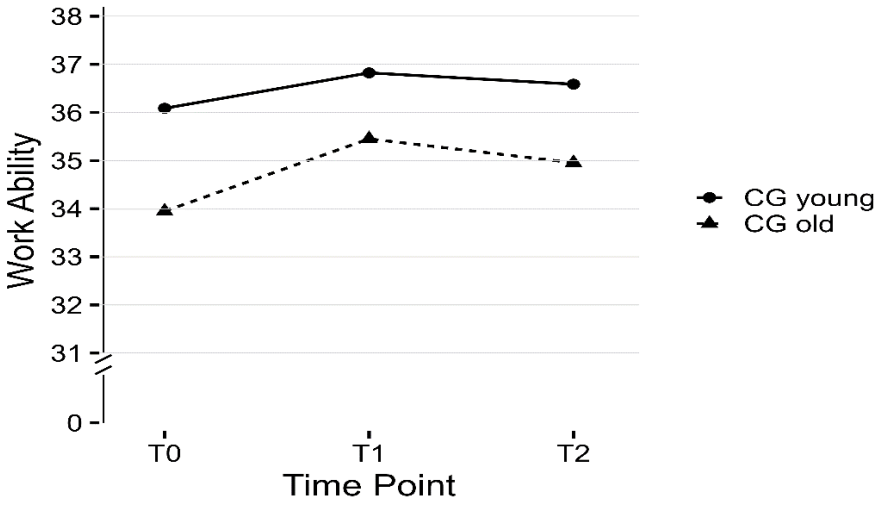



Figure 9: Development in the intervention group in mental health

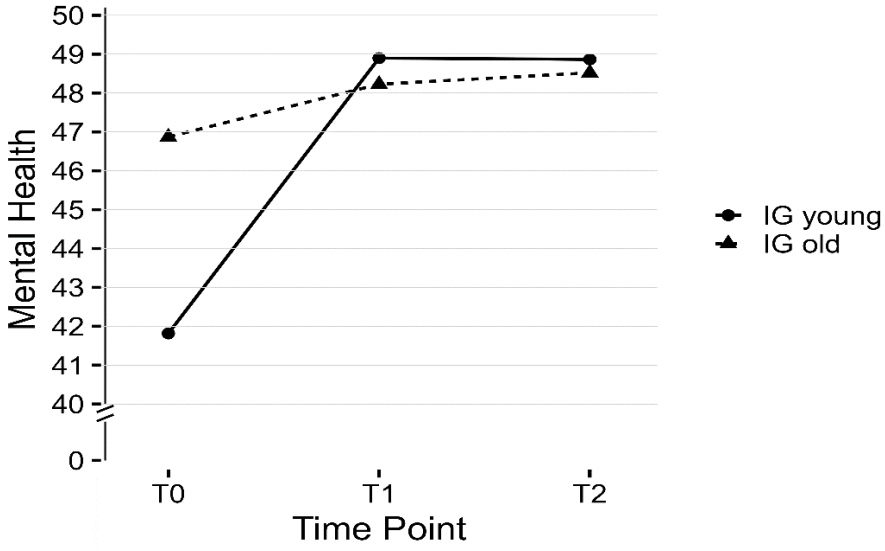
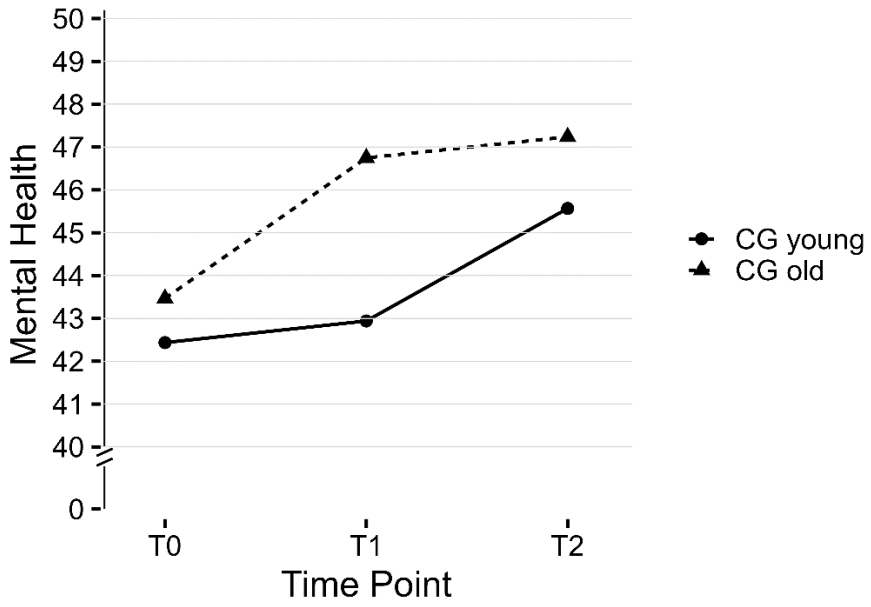


Figure 10: Development in the control group in mental health




# Discussion

The promotion of employees' well-being and productivity is crucial for our society as well as organizations, pointing to the need of research on interventions that can enhance work ability, physical health, and mental health (Michie et al., 2017; Noraziani et al., 2013). With technological advancements, digital prevention interventions have become accessible to large segments of the population who may not have access to conventional prevention services (Graham et al., 2020). This study aimed to compare the effectiveness of a digital prevention intervention with a conventional prevention program, BETSI/RV Fit, regarding work ability, physical health, and mental health in professionals experiencing initial impairments, as well as to examine the role of age and gender on the effectiveness of the interventions.

The findings of this study suggest that both digital and conventional prevention programs had an effect on work ability. This is in line with previous research that has shown that digital interventions can lead to improvements in work ability (van Schaaijk et al., 2019). The initial steep increase in work ability in both groups during the first 12 weeks of the intervention is also consistent with previous studies that have reported rapid improvements in work ability following workplace interventions (Tuomi et al., 1997). The deceleration in the rate of enhancement of work ability, especially among the control group, over the ensuing 12-week period is consistent with earlier observations, indicating that continued interventions and aid may be necessary to sustain improvements in work ability. The standard regimen of Betsi/RV Fit incorporates a self-directed training phase in the latter half of the program, which may not offer an equivalent degree of direction and assistance as the supervised program during the initial 12 weeks. These findings are in accordance with previous research, which suggests that enduring advancements in work capacity may require ongoing support and intervention (Gram et al., 2012). The age-specific effects found in this study are also consistent with previous research, suggesting that age can influence the effectiveness of workplace interventions on work ability (Söderbacka et al., 2020).

The present study did not find a significant effect for either time, group, or interaction on physical health, even when age and gender were included in the analyses. These results suggest that the effects of preventive interventions, whether digital or conventional, may require more time to develop an impact on physical health. Therefore, longer-term interventions and observations may be necessary to uncover any potential effects on physical health. This finding is consistent with previous research that has highlighted the importance of long-term interventions in improving physical

health outcomes (Fong Yan et al., 2018). Moreover, it has been suggested that digital interventions may have the potential to improve physical health outcomes over a longer period of time (Velardo et al., 2017). Nonetheless, more research is needed to determine the long-term effects of preventive interventions on physical health.

For mental health, the results of the present study revealed a significant time effect in the form of both a linear and a quadratic trend. Specifically, there was an initial steep increase in mental health during the first 12 weeks of the prevention programs, followed by a slower increase in the second half of the programs. These findings suggest that the first 12 weeks of the interventions are crucial for achieving significant improvements in mental health. For the control group, this suggests that there is a slower improvement in mental health after the end of personal assistance in the training phase and with the beginning of the self-initiation phase. Interestingly, this slowdown also occurs in the intervention group. A separate study would be needed to explain this phenomenon. Moreover, the linear trend remained significant even when age and gender were included in the analysis of variance. This finding is consistent with prior research suggesting a linear relationship between the duration of interventions and mental health outcomes (Heinze et al., 2021).

The present study's findings demonstrated that the effects of digital and conventional prevention interventions on work ability and mental health were moderated by age. Specifically, younger participants exhibited a greater improvement in work ability and mental health following the digital prevention intervention, while older participants benefited more from the conventional prevention intervention. These findings are in line with prior research that has identified age as a significant factor influencing the efficacy of digital interventions for mental health (Pywell et al., 2020). It is possible that older adults may experience more barriers to using mobile-based mental health interventions, such as concerns about technology literacy, privacy, and security, and may prefer more conventional, face-to-face interventions (Oh et al., 2021). Conversely, younger adults may be more comfortable and familiar with digital technology and therefore may benefit more from digital interventions. Nonetheless, these findings highlight the importance of tailoring interventions to different age groups in order to maximize their effectiveness and reach. Future studies could explore how to further adapt digital interventions to meet the unique needs and preferences of older adults as well as how to overcome potential barriers to their use.

The present study provides valuable insights into the effectiveness of a digital and conventional prevention program on work ability, physical health, and mental health outcomes. However, there are limitations to consider. Firstly, the quasi-experimental design of the study may limit its generalizability. A randomized controlled trial would have been more appropriate to test the effectiveness of the prevention program rigorously. Secondly, the absence of a control group without any prevention program may have allowed unknown factors to influence the interventions' effects, and therefore, the effects cannot be solely attributed to the interventions. Thirdly, the small sample size may have impacted the study's statistical power. Increasing the sample size would have allowed for greater precision in estimating the effects of the prevention programs. Forthly, a notable limitation of this study is the dropout rate of approximately 30%, which, although found to be non-systematic, leaves unanswered questions about the underlying reasons for participant withdrawal. This absence of detailed insight into the causes of dropout impacts the generalizability of the findings and indicates area need for qualitative research to better understand and reduce potential barriers for participation. Lastly, the lack of follow-up assessments is an important limitation, as it is unclear whether the improvements in work ability and mental health observed during the intervention phase would persist over time. Future research should conduct long-term follow-up assessments to determine the sustainability of the prevention program's effects.

This study on the effectiveness of digital and conventional prevention programs has important implications for both research and practice. For research, the study highlights the importance of utilizing rigorous research designs, such as randomized controlled trials, and increasing sample sizes to improve the validity and generalizability of study findings. Future research should also incorporate follow-up assessments to examine the sustainability of intervention effects over time. For practice, the study suggests that both digital and conventional prevention programs can be effective in improving work ability and mental health. However, it is important for practitioners to carefully consider the characteristics of their target population and to select the most appropriate prevention program for their needs. The findings indicate that a digital intervention shows particular promise for younger individuals, while older individuals are more likely to benefit from conventional interventions. Nonetheless, it is possible that age-specific effects will diminish as older populations become more accustomed to digital technologies.

# Conclusion

The results of the study suggest that prevention programs, both digital and conventional, have the potential to improve work ability and mental health outcomes. This improvement is particularly evident in the early stages of the intervention. The study highlights the importance of taking age-specific factors into account when designing and implementing these programs. However, the study's limitations, such as the small sample size, quasi-experimental design, and lack of follow-up assessments, must be recognized. Future research addressing these limitations could provide a more comprehensive understanding of the effectiveness of prevention programs in promoting work ability and physical and mental health outcomes. In summary, this study provides useful insights into the effectiveness of prevention programs and emphasizes the need for further research.

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# Chapter III – The Impact of a Digital Rehabilitation Aftercare on Health

Study 2: Impact of Digital and Conventional Rehabilitation Aftercare on Physical and Mental Health in Orthopedic Patients in Germany

Slightly modified version of the published manuscript:

Schmidt, D., Fritsch, J., Feil, K., Weyland, S., Rittmann, L. M., & Jekauc, D. (2024). Impact of digital and conventional rehabilitation aftercare on physical and mental health in orthopedic patients in Germany. *Frontiers in Public Health, 12*, 1344063. DOI: 10.3389/fpubh.2024.1344063

## Abstract

The integration of digital interventions in health rehabilitation offers promising opportunities to improve patient outcomes. However, empirical studies comparing the effectiveness of digital and traditional rehabilitation interventions remain scarce. This study was designed to evaluate the impact of a digital aftercare program, compared to traditional aftercare and a control group, on both psychological and physical health outcomes in individuals undergoing orthopedic rehabilitation. Additionally, the study also aimed to examine the moderating effects of age and gender. The study employed a partially controlled trial design, engaging a cohort of 805 orthopedic patients, divided into: digIRENA (n=323, digital aftercare), IRENA (n=252, traditional aftercare), and a control group (n=230, without organized aftercare). Measurements took place at four different time points: baseline (start of the rehabilitation program), T1 (13 weeks after the start of rehabilitation, marking the midpoint of aftercare), T2 (26 weeks, marking the end of aftercare), and T3 (43 weeks, to assess the sustainability of aftercare effects). The SF-12 Health Survey was the primary data collection instrument for measuring trends in physical and mental health outcomes over these intervals using repeated measures ANOVA. The results show that rehabilitants in the digIRENA group participated for a longer period of time than rehabilitants in the IRENA group, while the two groups did not differ in terms of motivation at T0 and organized physical activity outside of aftercare at T3. A significant improvement in physical health outcomes was observed in all groups across time, with digIRENA participants showing the greatest improvement. For mental health, all groups showed initial improvements, with the digIRENA group showing the most pronounced increase at T2. Overall, there was a decline in the effects achieved four months after the end of aftercare. When age and gender were included as covariates, the time effect for mental health disappeared, showing a significant time * gender interaction due to significantly lower baseline scores of women compared to men. The results of the study show that digital interventions, in particular the digIRENA program, contribute to improving health rehabilitation outcomes. The digIRENA program and similar digital health interventions may offer potential for improving health rehabilitation aftercare.

## Introduction

Within the healthcare landscape, the German Pension Insurance (Deutsche Rentenversicherung) has systematically operationalized an array of rehabilitative interventions, both inpatient and outpatient, governed by the axioms of “rehabilitation before pension” and “rehabilitation before care” (Weyermann, 2018). Central to this rehabilitative framework is the objective of restoring individuals' functional capacities and enhancing occupational performances after health-related setbacks (Bethge et al., 2019). A secondary aim is the promotion of sustainable health behaviors and attenuation of detrimental lifestyle choices, thereby mitigating risks of disease relapse and overall health decline (Nowossadeck, 2019). Concurrently, demographic shifts indicate a diminishing working-age population, which poses dual challenges to the pension system. According to projections from the Federal Statistical Office (Bundesamt, 2022), the proportion of working-age individuals (20-66 years) is anticipated to recede from 62 % to 54 % by 2060, while the population aged 67 and above is projected to rise from 20 % to 28 %. These trends caused an investment of €7.11 billion in rehabilitative interventions by the German Pension Insurance in 2018, highlighting the importance of rehabilitation for labor market sustainability (Rentenversicherung, 2022).

The German healthcare system is characterized by its universal coverage, providing comprehensive health services to all citizens through a mix of statutory health insurance and private health insurance schemes. Central to this system's approach to rehabilitation is the German Pension Insurance, which plays a pivotal role in operationalizing rehabilitative interventions aimed at facilitating individuals' return to work and daily life activities. These interventions, governed by the principles of “rehabilitation before pension” and “rehabilitation before care,” emphasize the system's preventive and restorative focus (DRV, 2021). Although initial rehabilitative interventions have demonstrated efficacy, longitudinal studies suggest a significant decline in their beneficial effects over time (Hüppe & Raspe, 2005; Mittag et al., 2011; Schuler & Faller, 2022). This attenuation can be attributed to several factors, including the fading of initial motivation (Jekauc, 2015), challenges in maintaining new health behaviors in the absence of structured support (Jekauc et al., 2015), and the complex interplay of chronic conditions and lifestyle factors (Finne et al., 2019). Moreover, the effectiveness of rehabilitation is not only influenced by the content and delivery of the intervention but also by patients’ motivation and engagement, which are critical for sustaining long-term health benefits (Gard, 2001).

In response to this decline, the German Pension Insurance implemented the Intensified Rehabilitation Aftercare (IRENA) program. This program utilizes a multimodal approach, combining therapeutic methods from various disciplines to address an extensive range of conditions such as musculoskeletal, metabolic, cardiovascular, neurological, and psychological disorders (Deck & Theissing, 2022). Accredited therapists within the IRENA program are required to have a minimum of three years of professional practice, ensuring that patients receive high-quality care from experienced practitioners. Structurally, the IRENA program incorporates strategies for occupational reintegration while emphasizing long-term health-promoting behaviors. The holistic nature of the IRENA program is designed to not only facilitate physical recovery but also to address the psychological well-being of patients, thereby underscoring the intrinsic link between physical and mental health in rehabilitation contexts. Physical rehabilitation is crucial for restoring function, improving mobility, and alleviating pain, which directly impacts an individual's quality of life and mental health by enhancing self-efficacy, reducing stress, and mitigating the risk of depression often associated with physical ailments (Lamprecht et al., 2012). Empirical data underscores the growing use of IRENA services, as reflected in the increasing number of approved aftercare interventions (Rentenversicherung, 2022).

However, despite its comprehensive endeavors, the IRENA program has notable limitations in terms of accessibility and adaptability to individual needs (Lamprecht et al., 2012). Empirical evidence suggests that both inpatient and outpatient paradigms lack sufficient spatiotemporal flexibility (Knapp et al., 2020). Barriers such as occupational obligations, geographical remoteness, rigid schedules, and family responsibilities may impede access to the program. These challenges are exacerbated in rural areas where accessing aftercare facilities within a reasonable time becomes problematic. In addition, the rigid schedule of the IRENA program often conflicts with work commitments in areas such as hospitality and leisure, as well as family responsibilities including caregiving and childcare. This lack of flexibility can hinder the overall effectiveness of the rehabilitation process, potentially affecting patients' motivation to engage and adhere to the aftercare program.

The incorporation of telerehabilitation technologies represents a viable strategy to enhance accessibility and offer a more person-centered approach by leveraging digital technologies. Using telecommunication technologies, telerehabilitation creates a more flexible healthcare delivery model, substantially reducing geographical and conflicting activities – factors particularly salient in rural areas and among populations with irregular working hours (Gigerenzer et al., 2016). This innovation could not only facilitate access to rehabilitation services, but also meet the motivational needs of patients by providing personalized and engaging digital content (Barak Ventura et al., 2019). However, research into telerehabilitation also highlights significant challenges, including technological accessibility issues, the need for digital literacy among participants, potential reductions in the personalization of care due to the absence of physical presence, and concerns regarding the privacy and security of health data (Leochico et al., 2020; Rabanifar & Abdi, 2021).

Meta-analytic evidence supports the equivalence of therapeutic outcomes between telerehabilitation and traditional face-to-face modalities for motor recovery and recovery from total knee arthroplasty (Agostini et al., 2015; Jiang et al., 2018). By adopting telerehabilitation technologies into the rehabilitation aftercare, one can overcome the inflexible parameters inherent to traditional programs such as IRENA, thereby facilitating a more individualized, adaptive intervention paradigm. Consequently, the operationalization of telerehabilitation programs could lead to considerable enhancements in the accessibility and adaptability of rehabilitation aftercare programs, contributing to the optimization of patient outcomes and the overall efficiency of the healthcare infrastructure.

When evaluating the effectiveness of telerehabilitation aftercare interventions, it is necessary to acknowledge the heterogeneity in implementation modalities, ranging from telephonic support to web-based platforms offering comprehensive therapeutic modules. A meta-analysis focusing on web-based applications for breast cancer patients found generally positive effects on specific indicators such as therapy-related menopausal symptoms and sleep function (Tokgöz & Dockweiler, 2021). However, these results were inconsistent with respect to other indicators such as health-related quality of life and cognitive functions. Studies conducted within Germany, such as the one by Ebert et al. (Ebert et al., 2013), have also reported positive results, demonstrating that patients who participated in web-based aftercare programs in addition to conventional approaches such as IRENA were more effective in stabilizing the treatment outcomes over a 12-month period. However, there remains a research gap, particularly concerning a detailed exploration of telerehabilitation's effectiveness in aftercare settings. This includes aspects often overlooked in previous studies, such as comprehensive comparisons with control groups and a focused examination of both psychological and physical health outcomes.

The primary objective of the present study was to compare the effectiveness of the digital rehabilitation aftercare with traditional IRENA and a control group on physical and mental health outcomes among patients undergoing orthopedic rehabilitation. Additionally, the study aimed to examine the moderating effects of age and gender, as these variables have been shown to be predictors of physical and mental health (Lin et al., 2022) and as possible moderating effects of age on intervention effectiveness have been demonstrated (Gallagher et al., 1997).

# Methods

## Design of the Study

The protocol for this study design has been published (Jekauc et al., 2021). A semi-randomized, longitudinal study design was used including three different study groups: traditional IRENA, digIRENA (digital IRENA), and a control group. All participants met the legal criteria for post-rehabilitation IRENA eligibility. The allocation of participants to the groups took place during their initial consultation with the responsible doctor at a rehabilitation clinic. Those rejecting IRENA participation were randomly allocated to either the digIRENA or control group. Sealed envelopes were used for the randomization procedure and the participants knew their group only after opening the envelopes. These envelopes were evenly distributed across the clinics to achieve a balanced 1:1 ratio between the digIRENA and control groups. It is important to note that, due to the transparent nature of the aftercare interventions, neither participants nor staff could be blinded to group allocation. Additionally, it was observed that some participants opted not to participate in the study upon learning they had been assigned to the control group rather than the digIRENA group, indicating a preference for the digital rehabilitation aftercare option. To increase the motivation to participate in the study, the participants that completed all four measurements received a 50 Euro Amazon voucher. Participants were initially recruited from three multiple rehabilitation clinics belonging to DRV Knappschaft-Bahn-See and the plan was to recruit from January 2020 until October 2020. However, recruitment was interrupted due to COVID-19 and also after the interruption there was a reduced admission in the rehabilitation clinics. For this reason, in August 2020 two more rehabilitation clinics joined and a one-year recruitment extension was authorized until October 2021. Because the number of sufficient participants was reached, the recruitment ended in August 2021. Although the initial plan was to recruit 1150 participants at baseline (Jekauc et al., 2021), the dropout was less than expected and therefore the recruitment stopped when 1060 participants were recruited.

The study comprised four measurement time points: pre-aftercare (T0), at 13 weeks post-initiation of aftercare (T1), at 26 weeks or the assumed end of aftercare (T2), and a 17-week post-aftercare follow-up (T3). These measurement intervals were strategically selected to capture the midpoint (T1), endpoint (T2), and a four-month follow-up (T3). It is critical to acknowledge that this schema represents an idealized timeline as deviations occurred due to varying starting time points and inconsistent adherence to the aftercare programs. Data collection included in-clinic questionnaires at T0 and subsequent mail or email sending of questionnaires at T1, T2, and T3, accompanied by a two-week non-response follow-up reminder. The study has been formally registered with the German Register of Clinical Studies under the identifier DRKS00022467. Ethical approval and data protection compliance have been obtained from the Ethics Committee and the Data Protection Officer at the Karlsruhe Institute of Technology.

## Sample

Power calculations indicated the necessity for 573 participants to assess telerehabilitation aftercare effectiveness, assuming a small effect size (Cohen's f = 0.07) due to limited robust empirical studies in this area (Agostini et al., 2015). With an alpha error set at 0.05 and a desired test power of 0.80, this sample size is required when using analysis of variance with repeated measurement. Anticipating a dropout rate of about 30 % per measurement point, the study initially aimed to enroll approximately 1,150 patients. Finally, because drop-out was lower than expected, 1,060 orthopedic rehabilitation patients were recruited at the baseline measurement (T0). In our study, we specifically targeted patients undergoing orthopedic rehabilitation, reflecting our primary aim to assess the effectiveness of digital and traditional aftercare within a cohort primarily affected by musculoskeletal disorders. Participants were recruited from five distinct rehabilitation clinics, ensuring a diverse sample representative of individuals undergoing orthopedic treatment. During their rehabilitation stay, the study's objectives and procedures were outlined to potential participants in a medical consultation, where study information and consent forms were provided. Those who agreed to participate completed the questionnaire either during their hospital stay or directly after discharge. A key inclusion criterion was a sufficient command of the German language, ensuring that all participants could complete the questionnaire independently without requiring external assistance. Attrition occurred over the course of the study, with four participants withdrawing consent for data utilization (two from digIRENA, one from traditional IRENA, and one from the control group). Thus, at T0 the sample consisted of 405 individuals in the digIRENA intervention cohort (145 females, representing 35.8 %), 352 in the traditional IRENA cohort (120 females, 34.1 %), and 299 in the control cohort (79 females, 26.4 %). With relevance for the analysis of the present study, there were 805 participants who filled out the questionnaires at all four measurement occasions. From these, 323 were in the digIRENA group, 252 in the IRENA group, and 230 in the control group.

## Measures

### Health

Health-related variables were assessed using the SF-12 Health Status Questionnaire, an abbreviated version of the SF-36 (Morfeld et al., 2011). This instrument comprises two subscales that delineate physical and mental health dimensions. The SF-12 has been empirically validated as a robust tool for measuring subjective health states, independent of an individual's current health status (Morfeld et al., 2011). The instrument employs a diverse array of response formats, including Likert scales as well as binary options. In calculating the SF-12 scores, we followed the original methodology proposed by Ware et al. (Ware et al., 1996). This decision was made to align with international research standards, facilitating comparability across studies. However, it is crucial to acknowledge that alternative scoring methods exist, such as those proposed by Wirtz et. (Wirtz et al., 2018a, 2018b). In relation to reliability metrics, existing literature reveals an internal consistency of Cronbach’s alpha = 0.83 for the Physical Health subscale and of 0.87 for the Mental Health subscale (Morfeld et al., 2011). With regard to content validity, the phrasing of the questionnaire items has been adjudicated as both comprehensible across diverse samples (Bullinger & Kirchberger, 1998).

### Participation in Aftercare

The participants of both the IRENA and digIRENA groups were asked if they had commenced their aftercare sessions since discharge from the respective clinic. For those who had already begun their aftercare, further inquiries were made regarding the number of weeks they participated in at least one aftercare session (i.e., the frequency of attendance) and the average duration spent in minutes per week attending these sessions (i.e., the duration of training). From these responses, the overall engagement in aftercare activities (in minutes) was calculated and compared between the two aftercare groups. For the purposes of this study, only the data at time t3 were analyzed, as this contained information on the extent of participation over the entire aftercare period.

### Participation in Other Structured Physical Activities

To comprehensively assess physical activity beyond the scope of rehabilitation aftercare, we incorporated three specific survey items targeting all participant groups. The first item queried participants on their involvement in any structured physical activities external to the designated aftercare programs. The subsequent item detailed the type of physical

activities engaged in, while the third item captured the average weekly duration of these activities. For the purpose of this study, the first and third items were utilized at the second time point (t2) to estimate the overall duration of structured physical activity throughout the rehabilitation aftercare period. Data on the average duration of such activities, reported in minutes per week, were then incorporated into our analyses to account for additional physical engagements outside the primary aftercare interventions.

### Motivation

Motivation was assessed using the German translation of the Behavioral Regulation in Exercise Questionnaire-2 (BREQ-2) (Markland & Tobin, 2004). This questionnaire consists of 19 items with a 5-point response format, designed to measure five different types of motivational regulation: (1) intrinsic motivation, (2) identified regulation, (3) introjected regulation, (4) external regulation, and (5) amotivation. In addition to these distinct motivational forms, the Relative Autonomy Index (RAI) can be calculated, which represents the degree of self-determination an individual exhibits towards a behavior (Markland & Tobin, 2004). The RAI was calculated by multiplying the scale value of intrinsic motivation by three, identified motivation by two, introjected regulation by negative one, external motivation by negative two, and amotivation by negative three, then summing all five scale values. Regarding reliability, the internal consistency (Cronbach's α) for the amotivation scale was 0.60, external regulation was 0.77, introjected regulation was 0.77, identified regulation was 0.83, and intrinsic regulation was 0.88 (Mahony et al., 2019). In terms of validity, it has been demonstrated that the subscales correlate with each other in a theoretically consistent manner, and higher self-determined motivations are associated with a greater likelihood of engaging in health behaviors (Mahony et al., 2019). This questionnaire was applied exclusively to the digIRENA and traditional IRENA groups to measure their motivation regarding participation in aftercare sessions. In order to determine the initial motivation of the participants, we only analyzed the information at t0 for the purposes of this study.

## Intervention

All participants in the study were offered IRENA intervention, and those subjects who declined to participate in IRENA were randomly assigned to either the digIRENA group or the control group. Two intervention programs were implemented in this study: Traditional IRENA and digIRENA. Participants in both intervention programs were under the continuous supervision of accredited therapists. In the case of adverse outcomes, participants were referred for additional treatment. Additionally, a control cohort was established, without a prescribed aftercare intervention.

### Traditional IRENA

Every rehabilitant in Germany has a right to rehabilitation aftercare such as IRENA following rehabilitation. In general, IRENA courses are offered in health centers or clinics spread throughout the country and rehabilitants have the opportunity to register for these courses. The traditional IRENA program permits a maximum of 24 therapeutic sessions with a duration of 90 to 120 minutes each. The IRENA program covers treatments from at least two therapeutic fields or chapters of the Classification of Therapeutic Services in Medical Rehabilitation (KTL; Klassifikation thereapeutischer Leistungen in der medizinischen Rehabilitation), making it interdisciplinary and involving multiple professional groups. It serves insured individuals who need exercise for functional limitations and also require lifestyle and behavior stabilization through structured education. This approach combines therapeutic and psychoeducative services, involving both movement therapists and psychologists.

For musculoskeletal disorders, the IRENA concept is tailored to those rehabilitants who require a combination of treatment elements from different therapeutic directions and specific care, monitoring, and therapy in a specialized facility (DRV, 2021). The therapeutic activities within IRENA for musculoskeletal conditions might include, but are not limited to: i) Group physiotherapeutic treatments focusing on musculoskeletal diseases, ii) Water-based physiotherapeutic treatments for musculoskeletal conditions, iii) Psychologically oriented group work targeting specific disorders, and iv) Structured education on managing non-inflammatory diseases of the musculoskeletal system or chronic pain. This comprehensive approach aims at not just addressing the physical aspects of musculoskeletal disorders but also at managing the psychological impacts, thereby fostering a holistic recovery process. The emphasis is on enhancing functionality, reducing pain, and improving the overall quality of life while also addressing the psychological

aspects such as coping strategies for pain management and fostering a proactive approach towards maintaining health (DRV, 2021).

### digIRENA

The Digital Intensified Rehabilitation Aftercare (digIRENA) program represents an innovativeadaptation of the established IRENA framework, incorporating digital technologies to improve the reach, customization, and participant engagement in post-rehabilitative care. Aimed at overcoming the barriers associated with traditional aftercare models, digIRENA introduces a tele-rehabilitation approach that offers flexibility, accessibility, and a focus on the patient's experience. This is particularly beneficial for individuals hindered by geographical distance, physical limitations, or scheduling conflicts.

The core of digIRENA is the use of the Caspar app (https://caspar-health.com/en-us), which provides 24 flexible telerehabilitation sessions of up to 90 minutes each. The integration of Caspar into the patient treatment begins during their inpatient treatment, preparing them for a smooth transition to self-directed training under remote therapeutic supervision once discharged. The service suite of digIRENA is designed to meet the rehabilitation needs of patients with musculoskeletal and other conditions, offering digital therapeutic modules that encompass virtual physiotherapy, educational content on lifestyle and disease management, and platforms for psychological support, all accessible from any location.

The transition from inpatient care to digIRENA's telerehabilitation is facilitated by Caspar's comprehensive patient information transfer protocol, ensuring continuity of care. The telerehabilitation sessions are structured, featuring a combination of visual, auditory, and animated guidance, and are designed to encourage ongoing dialogue between the patient and the therapist. This interactive setup allows for the personalized adaptation of the rehabilitation plan based on direct feedback. The Caspar platform provides a robust system for tracking and documenting patient engagement and progress, including a feature for patients to record and share videos of their exercise performance. This input is centrally monitored through a "therapist dashboard," enabling therapists to make immediate adjustments to the rehabilitation plan as needed.

### Control Group

Participants in the control group were initially offered the opportunity to participate in the traditional IRENA program, but chose not to do so. Due to the random draw, they were not assigned to the digIRENA intervention and therefore did not receive any structured aftercare. However, this group retained the option to participate in physical activity programs, including participation in community-based rehabilitation or general exercise programs.

## Statistical Analyses

The acquired dataset underwent preliminary data processing prior to analysis. In a first step, missing data were analyzed separately for each measurement time point using Little's MCAR test to determine the extent to which systematic missingness was present (Little, 1988). Missing values at the item level were imputed utilizing an Expectation-Maximization algorithm (Dempster et al., 1977), an iterative procedure consisting of expectation and maximization steps that converge upon a local maximum likelihood estimate (Jekauc et al., 2012). Post-imputation, values were rounded to the nearest integer. In cases where fewer than 50 % of the required values were available for a given scale score, missing value imputation was precluded, and the corresponding sum score was reported as 'missing,' thereby excluding the data from subsequent analyses. The differences between the three groups in terms of dropout rate between t0 and t3 were analyzed using the chi-squared goodness of fit test. One participant who self-identified as "diverse" in gender was excluded from analyses using age and gender as covariates.

An intention-to-treat analysis was employed, encompassing all individuals who consented to participate in the study and for whom data were available. Descriptive statistics were presented with regard to the distribution of gender, age, nationality, employment status, participation in aftercare, and motivation. To examine the differences between the digIRENA group and the IRENA group in terms of motivation and attendance, t-test and Welch test were used. Thereafter, repeated measures analyses of variance (ANOVA) were conducted to interrogate longitudinal trends in dependent variables, specifically subjective physical, and subjective mental health metrics as assessed by the SF-12

questionnaire (Hays, 1994). ANOVA was used across all four measurement occasions to assess the effects of the aftercare intervention and its durability. The sphericity assumption was tested using the Mauchly test and, in case of violation, the Greenhouse-Geisser adjustment was used to correct for violations of sphericity. To accommodate the challenges posed by unbalanced sample sizes in our ANOVA analysis, we employed both Type II and Type III ANOVA, ensuring the robustness of our findings across the digIRENA, IRENA, and control groups. The similarity of results between these analyses suggests that our conclusions are reliable and unaffected by the choice of analytical method. Initial group allocation biases based on age and gender variables were examined through logistic regression. In a separate ANOVA, the study examined the interaction of time, group, and age, based on the study by Schmidt et al. (Schmidt et al., 2023), where such an interaction suggested that younger participants benefited more from digital prevention programs, while older participants benefited more from traditional approaches. For this analysis, median split was performed for the variable age. For all three groups, the mean curves over the four measurement time points were presented graphically, with the 95 % confidence interval for each mean value. In case an interaction was significant, additional figures were presented. All analyses were performed at the 5 % significance level using SPSS version 28.

# Results

## Missing Data and Descriptive Statistics

Analysis of missing values for the SF-12 at the first measurement time point revealed that there were 51 missing values (0.40 %) across 33 (3.13 %) of all 1056 participants, affecting all 12 items. Little's MCAR test yielded a non-significant result ($\chi^2$=164.2; *df* = 166; *p* = 0.53), suggesting that the missing data were completely random. At the second measurement time point, there were 26 missing values (0.24 %) across 16 (1.76 %) of the 907 participants, affecting 9 out of 12 items. Little's MCAR test yielded a non-significant result ($\chi^2$ = 91.7; *df* = 133; *p* = 1.00), supporting the hypothesis of missing completely at random data. At the third measurement time point, there were 18 missing values (0.17 %) across 12 (1.39 %) of the 866 participants, affecting 9 out of 12 items. Little's MCAR test showed a non-significant result ($\chi^2$ = 87.319; *df* = 75; *p* = 0.16), supporting the MCAR assumption. At the fourth measurement time point, there were 32 missing values (0.31 %) across the 21 (2.46 %) of the 853 participants, affecting 10 out of the 12 items. Little's MCAR test was non-significant ($\chi^2$ = 118.2; *df* = 132; *p* = 0.80), also supporting the MCAR hypothesis. The dropout rate did not significantly differ between digIRENA group (16.3%), IRENA group (22.8%), and the control group (19.1%) ($\chi^2$ = 5.1; *df* = 2; *p* = 0.08).

The demographic profile of the sample showed that approximately two-thirds (67.3 %) were male, with the control group having the highest proportion at 73.6 % (see Table 5). The mean age of the participants was 54.2 years, with the oldest participants in the control group (M = 55.7 years) and the youngest in the digIRENA group (M = 53.0 years). A vast majority of participants were German nationals (97.6 %). More than three quarters (77.7 %) were employed full-time. At the last measurement time point (t3), the participants in the digIRENA group (*M* =1836 min; *SD* = 548 min) participated significantly more in the aftercare (*t* = 5.1; *df* = 317.6; *p* < 0.01) than the participants in the IRENA group (*M* =1492 min; *SD* = 826 min).

Table 5: Sample Characteristics at T0.

| | digIRENA | IRENA | Control | overall |
|---|---|---|---|---|
| overall | 405 (100 %) | 352 (100 %) | 299 (100 %) | 1056 (100 %) |
| Gender | | | | |
| male | 260 (64.2 %) | 231 (65.6 %) | 220 (73.6 %) | *711* (67.3 %) |
| female | 145 (35.8 %) | 120 (34.1 %) | 79 (26.4 %) | *344* (32.6 %) |
| divers | 0 | 1 (0.3 %) | 0 | *1* (0.1 %) |
| missing | 0 | 0 | 0 | *0* |
| Age | | | | |
| Mean | 53.00 | 54.21 | 55.74 | *54.18* |
| Standard deviation | 8.75 | 7.90 | 6.30 | *7.91* |
| n | 405 | 351 | 299 | *1055* |
| Missing | 0 | 1 | 0 | *1* |
| Nationality | | | | |
| German | 398 (98.3 %) | 339 (96.3 %) | 294 (98.3 %) | *1031* (97.6 %) |
| Non-German | 7 (1.7 %) | 11 (3.1 %) | 4 (1.3 %) | *22* (2.1 %) |
| Missing | 0 | 2 (0.6 %) | 1 (0.3 %) | *3* (0.3 %) |
| Employment Status | | | | |
| Full-Time (> 34 h) | 318 (78.5 %) | 265 (75.3 %) | 238 (79.6 %) | *821* (77.7 %) |
| Part-Time (15-34 h) | 47 (11.6 %) | 43 (12.2 %) | 26 (8.7 %) | *116* (11.0 %) |
| Part-Time (< 15 h) | 6 (1.5 %) | 2 (0.6 %) | 3 (1.0 %) | *11* (1.0 %) |
| Maternality/Leave | 0 | 0 | 0 | *0* |
| Education | 2 (0.5 %) | 2 (0.6 %) | 0 | *4* (0.4 %) |
| Unemployed | 32 (7.9 %) | 37 (10.5 %) | 32 (10.7 %) | *101* (9.6 %) |
| Missing | 0 | 3 (0.9 %) | 0 | *3* (0.3 %) |
| Participation in aftercare | | | | |
| Mean | 1836.24 | 1491.92 | | |
| Standard deviation | 545.84 | 825.88 | | |
| n | 263 | 196 | | |
| Missing | 76 | 76 | | |
| Participation in other structured physical activities | | | | |
| Mean | 80.8 | 85.3 | 85.4 | *83.5* |
| Standard deviation | 74.3 | 120.4 | 87.9 | *95.0* |
| n | 331 | 270 | 236 | *837* |
| Missing | 74 | 82 | 63 | |
| Motivation | | | | |
| Mean | 11.84 | 12.39 | | |
| Standard deviation | 3.88 | 3.97 | | |
| n | 401 | 347 | | |
| Missing | 4 | 5 | | |

A one-way ANOVA revealed no significant differences in the duration of structured physical activities outside of rehabilitation aftercare among the groups ($F = 0.2$; $df_1 = 2$; $df_2 = 834$; $p = 0.78$). Specifically, the mean duration for the digIRENA group was 80.6 minutes per week ($SD = 74.3$), for the IRENA group it was 85.3 minutes per week ($SD = 120.4$), and for the control group it was 85.4 minutes per week ($SD = 87.9$). There were also no significant differences between the digIRENA group ($M = 11.84$; $SD = 3.88$) and the IRENA group ($M = 12.39$; $SD = 3.97$) when comparing motivation in terms of the relative autonomy index before the start of the aftercare ($t = 1.90$; $df = 746$; $p = 0.06$).

## Physical Health

The analysis incorporated data from a total of 805 participants who completed the SF-12 questionnaire at all time points. This included 323 participants from the digIRENA group, 252 from the IRENA group, and 230 from the control group (see Table 6). Figure 11 illustrates that the baseline mean scores were similar across the three groups, showing no significant differences ($F = 2.7$; $df_1 = 2$; $df_2 = 1052$; $p = 0.07$).

Table 6: Descriptive Statistics for Physical Health.

| | | T0 | | | | T1 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Group | n | M | SD | LL | UL | M | SD | LL | UL |
| digIRENA | 323 | 34.9 | 8.9 | 33.9 | 35.9 | 39.1 | 9.3 | 38.1 | 40.1 |
| IRENA | 252 | 34.5 | 8.2 | 33.5 | 35.5 | 37.9 | 9.4 | 36.8 | 39.1 |
| Control | 230 | 35.8 | 8.2 | 34.7 | 36.9 | 39.4 | 9.1 | 38.2 | 40.6 |
| | | T2 | | | | T3 | | | |
| Group | n | M | SD | LL | UL | M | SD | LL | UL |
| digIRENA | 323 | 40.6 | 9.7 | 39.6 | 41.7 | 40.7 | 10.1 | 39.6 | 41.8 |
| IRENA | 252 | 38.8 | 9.9 | 37.6 | 40 | 38.9 | 9.7 | 37.7 | 40.1 |
| Control | 230 | 38.6 | 9.3 | 37.4 | 39.8 | 39.2 | 10.2 | 37.9 | 40.5 |

*n* = number of subjects; *M* = Mean; *SD* = standard deviation

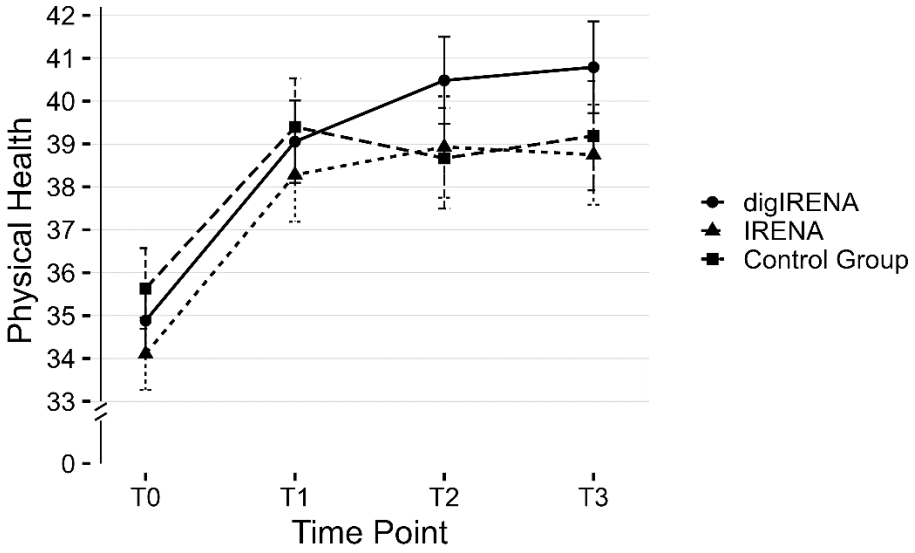
A significant main effect of time was observed (see Table 7), accounting for approximately 7.5 % of the within-subject variance ($F = 65.4$; $df_1 = 2.4$; $df_2 = 1955.0$; $p < 0.01$; $\eta^2 = 0.075$). Both the digIRENA and IRENA groups demonstrated a continuous increase in mean scores from T0 to T2, followed by a plateau (see Figure 11). In contrast, the control group exhibited an increase in mean scores from T0 to T1, after which a marginal decline was observed. A significant interaction effect for time * group was noted ($F = 2.5$; $df_1 = 4.9$; $df_2 = 1955.0$; $p = 0.03$; $\eta^2 = 0.006$), with the digIRENA group displaying a steeper incline in mean scores from T0 to T2 compared to the other two groups (see Figure 11). However, the effect size was rather small, explaining only 0.6 % of the variance in physical health.

Table 7: Analysis of Variance for Physical Health T0-T3.

| | SS | *df* | MSS | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Time | 10540.7 | 2.4 | 4324.1 | 65.4 | 0.00 | 0.075 |
| Time * Group | 812.6 | 4.9 | 166.7 | 2.5 | 0.03 | 0.006 |
| Error | 129321.5 | 1955.0 | 66.1 | | | |

*SS* = Sum of Squares; *df* = Degrees of Freedom; *MSS* = Mean Sum of Squares; *F* = F-Value; $\eta^2$ = Effect Size

Figure 11: Development of physical health from T0 to T3.




Note: All error bars represent 95% CI.

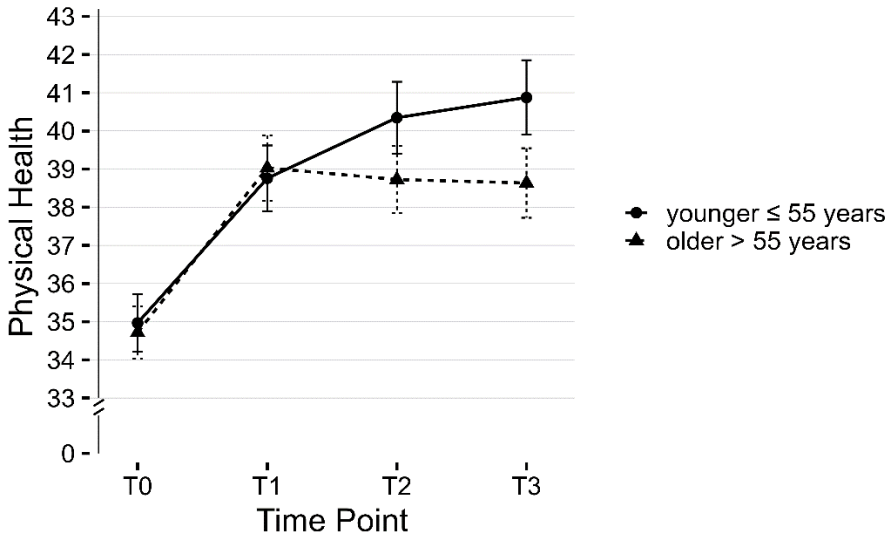
Upon incorporating age as a covariate and gender as an additional factor in the ANOVA model (see Table 8), the previously significant time * group interaction was no longer statistically significant ($F$ = 1.3; $df_1$ = 3.7; $df_2$ = 1526.3; $p$ = 0.29; $\eta^2$ = 0.003). In contrast, a significant time * age interaction emerged, explaining 0.9 % of the variance in physical health ($F$ = 7.6; $df_1$ = 1.8; $df_2$ = 1526.3; $p$ = 0.00; $\eta^2$ = 0.009). Using the median split for the age variable, the follow-up analyses showed a more continuous increase for the younger rehabilitants (≤ 55 years) across all four measurement time points, while for the older rehabilitants (> 55 years) there was a decrease in values from the second measurement time point (see Figure 12). In a separate ANOVA, we probed the three-way interaction effect of time * age * group, which yielded no significant results ($F$ = 0.4; $df_1$ = 4.9; $df_2$ = 1936.4; $p$ = 0.87; $\eta^2$ = 0.001).

Table 8: Analysis of Variance for Physical Health including Age and Gender.

| | SS | df | MSS | F | p | $\eta^2$ |
|---|---|---|---|---|---|---|
| Time | 2184.6 | 2.4 | 892.3 | 13.7 | 0.00 | 0.017 |
| Time * Age | 1464.4 | 2.4 | 598.1 | 9.2 | 0.00 | 0.011 |
| Time * Group | 344.8 | 4.9 | 70.4 | 1.1 | 0.37 | 0.003 |
| Time * Gender | 188.8 | 2.4 | 77.1 | 1.2 | 0.31 | 0.001 |
| Time * Group * Gender | 148.8 | 4.9 | 30.4 | 0.5 | 0.80 | 0.001 |
| Erorr | 127460.1 | 1951.3 | 65.3 | | | |

*SS* = Sum of Squares; *df* = Degrees of Freedom; *MSS* = Mean Sum of Squares; *F* = F-Value; $\eta^2$ = Effect Size

Figure 12: Development of physical health for age groups.




Note: All error bars represent 95% CI.

## Mental Health

Data were analyzed for a total of 805 participants who completed the SF-12 questionnaire at all measurement occasions. This included 323 participants from the digIRENA group, 252 from the IRENA group, and 230 from the control group (see Table 9). The results indicated that at baseline (T0), participants in the control group had significantly higher scores compared to both the digIRENA and IRENA groups, with digIRENA participants scoring higher than those in the IRENA group ($F = 4.0$; $df_1 = 2$; $df_2 = 1052$; $p = 0.02$). All three groups exhibited an increase from T0 to T1, reflected in a significant main effect of time that accounted for approximately 1.8 % of within-subjects variance (see Table 10). Participants in the digIRENA group demonstrated the steepest rise from T0 to T2 (see Figure 13). However, a decline in scores was observed for all groups beyond T2. Overall, the time * group interaction was not statistically significant ($F = 1{,}1$; $df_1 = 4.7$; $df_2 = 1890.7$; $p = 0.34$; $\eta^2 = 0.003$).

Table 9: Descriptive Statistics for Mental Health.

| | | T0 | | | | T1 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Group | n | M | SD | LL | UL | M | SD | LL | UL |
| digIRENA | 323 | 44.4 | 11.2 | 43.2 | 45.6 | 47.3 | 10.9 | 46.1 | 48.5 |
| IRENA | 252 | 43.2 | 11.4 | 41.8 | 44.6 | 46.1 | 11.0 | 44.7 | 47.4 |
| Control | 230 | 45.7 | 10.4 | 44.4 | 47.0 | 46.9 | 10.8 | 45.5 | 48.3 |
| | | T2 | | | | T3 | | | |
| Group | n | M | SD | LL | UL | M | SD | LL | UL |
| digIRENA | 323 | 48.2 | 10.7 | 47.0 | 49.4 | 47.3 | 11.2 | 46.1 | 48.5 |
| IRENA | 252 | 45.7 | 11.7 | 44.2 | 47.1 | 44.9 | 11.9 | 43.4 | 46.4 |
| Control | 230 | 47.3 | 10.8 | 45.9 | 48.7 | 46.9 | 10.7 | 45.5 | 48.3 |

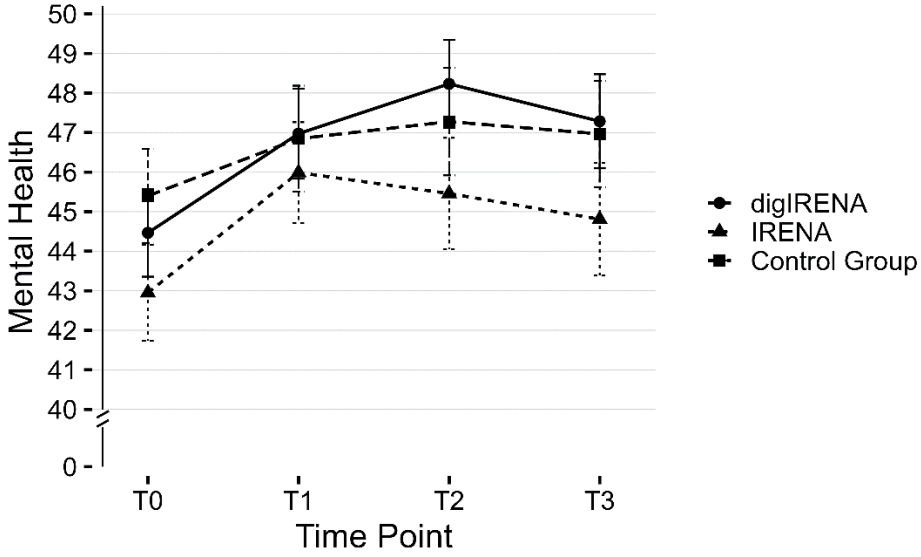
Note: *n* = Number of Participants; *M* = Mean; *SD* = Standard Deviation; *LL* = Lower Limit; *UL* = Upper Limit

Table 10: Analysis of Variance for Mental Health T0-T3.

| | SS | *df* | MSS | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Time | 3284.7 | 2.4 | 1393.3 | 14.3 | 0.00 | 0.018 |
| Time * Group | 519.6 | 4.7 | 110.2 | 1.1 | 0.34 | 0.003 |
| Error | 183634.0 | 1890.7 | 97.1 | | | |

Note: *SS* = Sum of Squares; *df* = Degrees of Freedom; *MSS* = Mean Sum of Squares; *F* = F-value; $\eta^2$ = Effect Size

Figure 13: Development of mental health from T0 to T3.




Note: All error bars represent 95% CI.

When age was included as a covariate and gender as an additional factor in the ANOVA, the main effect of time was not significant ($F = 1.0$; $df_1 = 2.3$; $df_2 = 1874.2$; $p = 0.39$; see Table 11). Notably, only the interaction of gender * group exhibited a significant effect ($F = 4.6$; $df_1 = 2.4$; $df_2 = 1874.2$; $p = 0.01$; $\eta^2 = 0.006$). Subsequent analyses revealed that this effect was attributable to female participants having significantly lower baseline scores compared to males. During the follow-up period, the mean scores for males and females converged. In a separate ANOVA, it was determined that the three-way interaction of time * group * age had no significant effect on mental health outcomes ($F = 1.9$; $df_1 = 4.7$; $df_2 = 1871.1$; $p = 0.09$; $\eta^2 = 0.006$).

Table 11: Analysis of Variance for Mental Health T0-T3 including Age and Gender.

| | SS | *df* | MSS | *F* | *p* | $\eta^2$ |
|---|---|---|---|---|---|---|
| Time | 221.8 | 2.3 | 94.3 | 1.0 | 0.39 | 0.001 |
| Time * Age | 38.0 | 2.3 | 16.2 | 0.2 | 0.88 | 0.000 |
| Time * Group | 367.4 | 4.7 | 78.1 | 0.8 | 0.54 | 0.002 |
| Time* Gender | 1040.8 | 2.4 | 442.6 | 4.6 | 0.01 | 0.006 |
| Time * Group * Gender | 319.8 | 4.7 | 68.0 | 0.7 | 0.62 | 0.002 |
| Error | 182138.5 | 1874.2 | 97.1 | | | |

Note: *SS* = Sum of Squares; *df* = Degrees of Freedom; *MSS* = Mean Sum of Squares; *F* = F-value; $\eta^2$ = Effect Size

# Discussion

The main aim of the present study was to evaluate the efficacy of a digital aftercare program in improving mental and physical health outcomes. Therefore, the study examined three groups: a digital aftercare group (digIRENA), a traditional rehabilitation aftercare group (IRENA), and a control group without an aftercare intervention. We aimed to determine not only the relative effectiveness of digIRENA in improving health indicators, but also how it compares to traditional aftercare approaches and the absence of aftercare.

A notable observation from our study was the improvement in physical health measures for both the IRENA and digIRENA groups, with a statistically significant increase in SF-12 physical health subscale scores contributing to approximately 7.5% of intraindividual variance. While the rate of improvement appeared slightly more pronounced in the digIRENA group, this finding warrants careful interpretation in light of the overall similarities between the groups and the observed decline in SF-12 scores after T1. Given the unique circumstances of the COVID-19 pandemic, which may have influenced participants' willingness to engage in traditional face-to-face programs, it is prudent to consider these factors when evaluating the relative effectiveness of digitized aftercare approaches. This context highlights the importance of digital health interventions as a complement to traditional care, especially in scenarios where conventional approaches may be less accessible.

While our findings indicate significant improvements in physical health measures for both the IRENA and digIRENA groups, it is crucial to contextualize these improvements in light of similar progress observed in the control group between T0 and T1. The control groups' enhancement, demonstrating a parallel pattern of improvement, raises important considerations regarding the specific contribution of the intervention programs. This observation compels us to carefully evaluate the extent to which the improvements in the intervention groups can be attributed solely to the program's effects, as opposed to natural recovery processes over time or general health trends among the study population. The presence of improvement in the control group suggests that factors beyond the structured aftercare contributed to health gains, which may include natural recovery, seasonal effects, or changes in individual health behaviors independent of our study interventions. Additionally, the participation of control group members in structured physical activities outside of the aftercare programs may also have contributed to the observed improvements in their health outcomes.

In terms of mental health, participants in the control group displayed higher baseline mental health scores compared to their counterparts in the digIRENA and IRENA groups. Such disparities at baseline, likely due to self-selection, could be explained by the randomization process and are similar to problems documented in other intervention studies (Bender et al., 2015). As reflected in the lower number of individuals that were initially in the control group compared to the digIRENA-group, there might have been an attrition bias. Although due to logistic reasons we did not keep track of these patterns, it might be that individuals who withdrew their willingness to participate in the study after they had been informed that they were in the control group might have had lower mental health scores than those who decided to stay in the study. While all groups demonstrated a marked improvement from T0 to T1, the digIRENA group showed the greatest increase at T2, mirroring the findings of Gold et al. (Gold et al., 2021) that underscore the accelerated benefits of digital interventions. Nevertheless, the absence of a significant interaction effect between time and group mitigates these observations.

In addition, one of the surprising findings of our study was the decline in mental health outcomes observed in all groups at four months after the end of the aftercare intervention. Although the digIRENA and IRENA groups maintained scores above their initial baseline, the general decline postulates a transient nature of the positive effects conferred by the rehabilitation. This trend aligns with findings of Winzer et al. (Winzer et al., 2018), who identified a diminishing effect of mental health interventions over time if not bolstered by ongoing support or periodic follow-up sessions. Similarly, Bond and colleagues (Bond et al., 2014) observed that the benefits of mental health interventions, especially in the context of rehabilitation, can be short-lived, emphasizing the significance of continued care and strategies to promote long-term mental well-being. Our results, in light of these previous studies, advocate for the integration of sustained, perhaps even aftercare concepts with refresher workshops at regular intervals to ensure enduring positive outcomes in mental health.

With the inclusion of age and gender into the analysis, the main effect of time disappeared. This observation parallels findings by Schmidt et al. (Schmidt et al., 2023), underscoring the importance of demographic variables in modulating responses to digital interventions. Notably, an interaction effect between time and gender was discerned. Women, who

had lower mental health scores than men at T0, manifested the most pronounced improvements throughout the rehabilitation period. This trend is consistent with the growing body of evidence highlighting gender-specific trajectories in response to mental health interventions (Bolea-Alamanac, 2017). Consequently, these insights emphasize the need to integrate gender-specific considerations when delivering rehabilitation programs.

In our analysis of mental health outcomes, it is crucial to consider the unique backdrop against which this study was conducted—the COVID-19 pandemic (Xiong et al., 2020). The absence of significant differences in mental health improvements across groups, despite the varied intervention modalities, may partly reflect the pervasive stress and uncertainty induced by the pandemic. This period has been marked by widespread reports of increased psychological distress across all demographics (Gloster et al., 2020), which could obscure the mental health benefits typically conferred by aftercare programs. The pandemic's impact could especially affect older adults, who not only were advised to avoid social contacts but also might have experienced heightened concerns for their health, further influencing their mental well-being and responsiveness to rehabilitation efforts.

For physical health, an interaction effect between time and age was revealed, indicating a heterogeneous response to the rehabilitation programs depending on age. Specifically, younger participants exhibited a sustained trajectory of improvement across all measurement occasions, whereas their older counterparts reached a plateau following an initial upswing. This finding that younger patients appear to benefit more from interventions aligns partially with findings in the broader rehabilitation literature. While Gosselin et al (Gosselin et al., 2007) found that intensive rehabilitation programs were equally beneficial for young and older participants, the study by Palmcrantz et al (Palmcrantz et al., 2012) found that younger individuals tended to receive more care and rehabilitation services, suggesting a possible inequity in the allocation of health resources. Nonetheless, it was observed that self-perceived global recovery did not significantly vary between different age groups.

The present study found that the three-way interaction of time, group, and age was not significant for both physical and mental health outcomes. This finding differs from that of Schmidt et al. (Schmidt et al., 2023), who reported that younger individuals derived greater benefits from digital prevention compared to their older counterparts. The absence of a significant interaction in our data suggests that the effectiveness of the digIRENA program may not be moderated by age, thus challenging the assumption that digital interventions are particularly advantageous for younger cohorts. This discrepancy emphasizes the complexity of age as a variable in the context of healthcare interventions and underlines the need for more nuanced investigations into the demographic-specific effects of digital rehabilitation programs.

An important consideration in our study's context is the overarching impact of the COVID-19 pandemic on both the implementation of aftercare programs and the mental health of participants. Our findings indicated that participants in the digIRENA group engaged significantly more in the aftercare program compared to those in the IRENA group. Since a significant body of research suggests that mental health can affect adherence (DiMatteo et al., 2000; Poletti et al., 2022), one might hypothesize that this increased engagement could be due to better mental health among digIRENA participants. However, our analysis revealed that the mental health scores at the onset of aftercare did not significantly differ between the digIRENA and IRENA groups, suggesting other factors influenced participants' engagement levels.

The flexibility offered by digIRENA, allowing for immediate commencement post-rehabilitation clinic stay, appears to be a critical factor in this increased participation. This advantage became particularly relevant during the COVID-19 pandemic when concerns about face-to-face interactions may have dissuaded participants from engaging with traditional IRENA sessions. Such apprehensions, along with logistical challenges presented by pandemic-related restrictions, underscore the importance of digital aftercare solutions like digIRENA, which bypass many of the barriers inherent to in-person treatment modalities. Moreover, the pandemic's effect on mental and physical health—a significant concern during this period—raises questions about the interplay between participants' health status, their motivation for aftercare participation, and the overall effectiveness of the interventions. The control group's higher baseline mental health scores compared to the intervention groups, and particularly the IRENA group's lower scores, highlight the importance of mental health in influencing treatment compliance and engagement.

Previous evaluations of the IRENA program, notably by Lamprecht et al. (Lamprecht et al., 2011, 2012), before the emergence of the COVID-19 pandemic, offer insights into its effectiveness in improving participants' health status. The 2011 study indicated that 79% of participants reported an improvement in their health status following IRENA, with significant enhancements in physical and mental health domains. However, these outcomes were based on retrospective data, with participants evaluating their condition improvement post-IRENA without a control group for comparison.

The 2012 study, which also lacked a control group, did not observe significant changes in health-related quality of life using the SF-12 one year post-IRENA, suggesting the potential for transient effects of the intervention. Comparing these previous findings to our current study, which includes a control group and pre-post measurements, offers a nuanced understanding of IRENA's effectiveness amid the pandemic. Our results suggest that while digital aftercare and traditional IRENA can both lead to improvements in physical and mental health outcomes, the context of COVID-19 has introduced unique challenges and considerations. Specifically, the increased engagement in digIRENA over IRENA may not solely be attributed to differences in health status but perhaps to the digital program's flexibility and ability to circumvent pandemic-related barriers to participation.

## Strengths and Limitations

The present study has several strengths. First, the large sample size supports the robustness of our findings, increasing their generalizability and reducing the margin of error inherent in smaller samples. Second, the use of validated measures to assess health outcomes was a strength. Moreover, the longitudinal design allows to assess the development of the individual indicators across time. Third, our study design included two intervention groups (digIRENA and IRENA) and a control group, which allowed us to estimate the effectiveness of digital aftercare. These methodological strengths allow for a comprehensive comparison of the digIRENA, IRENA, and control group.

However, several limitations need to be taken into account. Primarily, the adoption of partial randomization, necessitated by ethical considerations, introduces the possibility of self-selection bias. This bias may manifest as participants with limited digital proficiency opting for traditional IRENA. Secondly, as previously mentioned, the observed discrepancy in initial participant numbers between the digIRENA and control groups may indicate an attrition bias related to group allocation. These factors collectively highlight the challenges in achieving a perfectly balanced experimental design and necessitate a cautious interpretation of the findings within these constraints. Thirdly, the study design may not have captured the true intervention period, given the variability in the commencement of aftercare measures. Additionally, our exclusive reliance on self-report measures might have introduced biases. Incorporating objective metrics, such as actual days of work incapacity, could enrich future studies. Furthermore, we did not systematically collect data on the specific reasons participants declined participation in the traditional IRENA program. This oversight limits our ability to fully understand the range of factors influencing individuals' decisions against engaging with this aftercare option. Moreover, the unprecedented conditions of the COVID-19 pandemic introduced significant extraneous variables that may have impacted the study's outcomes. The pandemic's influence extended beyond the mere availability of traditional IRENA courses, potentially affecting participants' willingness to engage in face-to-face interventions due to health concerns. This could have led to a preferential decline in IRENA participation or suboptimal engagement during sessions, motivated by fears of contracting the virus. Moreover, the pandemic's pervasive impact on public health measures and personal well-being might have influenced both mental and physical health outcomes, introducing motivational deficits that hinder proper participation in the aftercare programs (Vindegaard & Benros, 2020). In addition, a notable limitation of our study is that the control group independently engaged in structured physical activities, effectively creating their own intervention. This unforeseen variable may have diminished the apparent effects of the structured IRENA and digIRENA programs, as the control group's self-directed activities contributed to health improvements that could mask the distinct benefits of the formal interventions. Finally, this study did not account for the varying contextual conditions of the participants, such as their living environments, availability of informal care, and social support systems. These factors could significantly influence rehabilitation outcomes by affecting patients' ability to engage with aftercare programs and adhere to recommended practices.

## Implications and Future Directions

The findings from this study have several implications for health rehabilitation research and its applied domains. One of the observations concerns the effectiveness of the digIRENA program, which highlights the potential of digital interventions in the rehabilitation sector (Agostini et al., 2015). In today's digital age, healthcare professionals have the opportunity to seamlessly integrate traditional rehabilitation methods with digital alternatives, allowing them to expand and improve aftercare services (Jekauc et al., 2021). This is particularly relevant when addressing the rehabilitation needs of younger cohorts, who are often more adept and receptive to technological interfaces (Goodyear & Armour, 2018). Moreover, the nuances in rehabilitation responses, as reflected in age and gender differences, underscore the urgency of individualized intervention designs. Relying on generalized, standardized approaches may inadvertently

attenuate the efficacy of interventions failing to take into account the heterogeneity of rehabilitation recipients (Onyeaka et al., 2021). Furthermore, it becomes imperative to delve deeper into understanding how digital aftercare influences different forms of motivation, including intrinsic and extrinsic motivation. Such exploration could unveil critical insights into how motivational factors contribute to the adherence and overall success of rehabilitation programs, offering guidance for the design of more effective, engaging, and personalized aftercare strategies.

Despite the observed benefits of the digIRENA program in our study, it is important to recognize the inherent limitations of telerehabilitation, which have been highlighted by existing research. Challenges such as technological barriers, the necessity for patient and provider digital literacy, potential reductions in the therapeutic relationship due to the absence of in-person interactions, and concerns regarding data security and privacy remain significant (Leochico et al., 2020; Rabanifar & Abdi, 2021). Moreover, the impersonal nature of digital interventions may not suit all individuals, especially those who derive substantial therapeutic benefit from direct human contact. While our findings suggest a role for telerehabilitation in expanding access to aftercare services, especially under constraints such as those imposed by the COVID-19 pandemic, these limitations underscore the need for a nuanced approach to integrating digital solutions into the rehabilitation continuum. It is essential to balance the benefits of digital aftercare with the value of traditional, face-to-face interactions, ensuring that rehabilitation programs are accessible, effective, and respectful of patient preferences and needs (Shenoy & Shenoy, 2018).

# Conclusion

The landscape of health rehabilitation is in a state of dynamic change, driven by the growing possibilities of digital interventions. The present study sought to compare the effectiveness of a novel digital aftercare program with its traditional counterpart and a control group. The results highlight not only the potential of digital modalities to improve rehabilitation aftercare outcomes, but also the intricate interplay of demographic variables such as age and gender in shaping these outcomes. The study demonstrates that digital interventions like digIRENA can be effective and serve as valuable complements to conventional aftercare methods. In addition, the observed temporary improvement in mental health outcomes highlights the need for interventions that provide ongoing support. By shedding light on these aspects, this research contributes to digital health research and invites further investigations in this promising field.

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# Chapter IV – The Impact of a Digital and Conventional Rehabilitation Aftercare on Work Ability

Study 2: Comparing the Effectiveness of Digital and Conventional Rehabilitation Aftercare on Work Ability in Orthopedic Patients - A Longitudinal Study in Germany

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## Abstract

Purpose. The primary aim of this study was to compare the effectiveness of digital rehabilitation aftercare (digIRENA) with conventional rehabilitation aftercare (IRENA) and a control group without organized aftercare in improving work ability among orthopedic patients.

Methods. A total of 1,056 orthopedic rehabilitation patients were recruited from multiple rehabilitation clinics in Germany and randomly assigned to three groups: digIRENA (n = 405), IRENA (n = 352), or a control group (n = 299). Work ability was assessed using the short version of the Work Ability Index at four time points: baseline, 13 weeks, 26 weeks, and 43 weeks. Repeated measures ANOVA was conducted to examine longitudinal trends in work ability, with additional analyses to assess the impact of age, gender, and employment status on outcomes.

Results. Work ability improved significantly over time in all three groups ($F = 37.6$, $p < 0.01$, $\eta^2 = 0.045$). The interaction between time and group was significant ($F = 2.2$, $p < 0.01$, $\eta^2 = 0.006$), favoring the digIRENA group. The digIRENA group showed the steepest improvement in work ability, particularly in the first 12 weeks, and continued to show gains in the second half of the follow-up period, while work ability in the IRENA and control groups stabilized. However, this interaction effect disappeared when age and gender were included in the analysis. Younger participants and -unemployed individuals showed greater improvements.

Conclusion. Digital rehabilitation aftercare was more effective than traditional aftercare in improving work ability. These findings support the integration of digital platforms into rehabilitation programs and emphasize the importance of fostering independent, self-initiated exercise post-rehabilitation to sustain long-term benefits.

## Introduction

Orthopedic rehabilitation, also referred to as rehabilitation for musculoskeletal diseases (MSDs), plays a crucial role in the recovery and reintegration of individuals affected by musculoskeletal disorders, fractures, joint replacements, and other orthopedic conditions (Greising et al., 2020). Globally, MSDs are leading contributors to work disability, affecting millions of individuals each year (Briggs et al., 2020). Orthopedic impairments often result in functional limitations that restrict an individual's ability to return to work, thereby affecting both personal livelihoods and broader economic productivity (Duong et al., 2022). Beyond economic implications, work is recognized as an important factor in promoting physical health, psychological wellbeing, and social inclusion (Waddell & Burton, 2006). Returning to work after rehabilitation has been shown to improve self-esteem, reduce symptoms of depression, and enhance overall quality of life (Wolfenden & Grace, 2009). Rehabilitation programs are thus essential, not only for improving physical functioning but also for restoring work ability, which is critical for maintaining labor force participation.

Orthopedic conditions, encompassing a wide range of MSDs, are particularly significant in Germany, contributing to 12% of long-term sick leave and early retirement (Leitlinien für die sozialmedizinische Begutachtung, 2017). MSD-related disabilities contributed to 888.9 million work disability days in 2022, resulting in an estimated €207 billion loss

in gross value added and €118 billion in economic production losses (BAuA, 2023). As the number of individuals aged 67 and above in Germany is projected to rise by 22%, from 16 million in 2020 to 20 million by 2035 (Bundesamt, 2021), preserving work ability through effective rehabilitation becomes an increasingly critical societal challenge. This age threshold is significant because 67 marks the standard retirement age in Germany, and ensuring work ability for those approaching or extending beyond this age is essential for maintaining workforce participation and addressing the challenges of an aging population.

In Germany, medical rehabilitation is an integral part of the healthcare system, with primary responsibility resting on the Deutsche Rentenversicherung (German Pension Insurance) for individuals of working age. This model emphasizes the principles of "rehabilitation before pension" to enable patients to reintegrate into the workforce and "rehabilitation before care" to prevent dependency on long-term care services (Lamprecht et al., 2012). Rehabilitation services typically encompass a three-week inpatient or outpatient program focusing on restoring physical and functional capacity, followed by tailored aftercare interventions to sustain and build upon the initial rehabilitation outcomes (Gerdes et al., 2006). The majority of orthopedic rehabilitation programs target musculoskeletal conditions such as osteoarthritis, back pain, fractures, and joint replacements (Bevan, 2015), which are among the leading causes of work disability in Germany (Porst et al., 2022).

In Germany, medical rehabilitation is highly structured and aims to achieve measurable improvements in functional capacity, quality of life, and work ability (Bethge et al., 2019; Schuler et al., 2019). Evidence from international systematic reviews highlights the effectiveness of multidisciplinary rehabilitation programs in improving physical functioning (Momsen et al., 2012), mental health (Dalton-Locke et al., 2021), and social reintegration (Storr et al., 2022) across various patient populations. These findings align with a meta-analytic results from German rehabilitation studies, which demonstrate substantial pre-post improvements in functional outcomes, particularly for musculoskeletal and psychosomatic conditions (Bethge et al., 2019). However, the meta-analysis emphasized the importance of tailoring rehabilitation interventions to patient-specific needs and the variability of outcomes across disease groups and patient demographics.

The restoration of work ability, defined as the balance between an individual's resources and the demands of their work environment (Tuomi et al., 1997), is a central goal of rehabilitation interventions. Work ability declines with age (Converso et al., 2018), posing an increasing challenge in light of demographic changes. Reduced work ability is associated with higher risks of early retirement (Sousa-Ribeiro et al., 2023) and long-term sickness absence (Notenbomer et al., 2015), making it a key determinant of both individual and societal well-being. Consequently, the German healthcare system, particularly through the German Pension Insurance, has implemented a range of rehabilitation interventions aimed at maintaining and improving work ability.

Although traditional rehabilitation programs, such as the intensive rehabilitation aftercare (IRENA) program, have demonstrated effectiveness in improving functional outcomes and reducing disability days (Lamprecht et al., 2011), there is growing interest in the potential utility of digital rehabilitation platforms. Digital rehabilitation may offer a spatially accessible and flexible alternative to conventional approaches, addressing the challenges of motivation and adherence that often arise after the completion of in-person rehabilitation programs (Schmidt et al., 2024). Studies have shown that rehabilitation has a positive effect on reducing early retirement and long-term sickness absence (Vandenbroeck et al., 2016). However, the impact of digital rehabilitation on work ability remains underexplored, and its effectiveness compared to conventional aftercare programs such as IRENA is not yet well established.

Given the significant socioeconomic implications of maintaining work ability and the potential for digital rehabilitation to enhance recovery, the current study aims to compare the effectiveness of digital rehabilitation aftercare with traditional IRENA and a control group on work ability in patients undergoing orthopedic rehabilitation.

# Methods

## Study Design

The study employed a quasi-experimental, longitudinal design to evaluate the impact of two rehabilitation aftercare approaches—digital and conventional—on work ability of orthopedic patients. Participants were allocated into three distinct groups: those receiving traditional aftercare, those enrolled in a digital aftercare program, and a control group

without structured aftercare (Jekauc et al., 2021). Data were collected at four intervals to monitor changes in work ability over time: at baseline (T0), midway through aftercare (T1), upon completion of the intervention (T2), and four months post-intervention (T3). This timeline was structured to allow for the assessment of both immediate and sustained effects of the rehabilitation interventions on work ability. The study was officially registered with the German Register of Clinical Studies under the identifier DRKS00022467. Ethical approval for the study was obtained from the Ethics Committee of the Karlsruhe Intitute of Technology, and data protection compliance was ensured with the guidance of the Data Protection Officer at the Karlsruhe Institute of Technology. All study procedures adhered to the relevant ethical guidelines, and informed consent was obtained from all participants prior to their inclusion in the study.

## Sample

Power calculations indicated that a sample of 573 participants was required to assess the effectiveness of telerehabilitation aftercare, assuming a small effect size (Cohen's $f = 0.07$) (Agostini et al., 2015). This calculation was performed with a significance level ($\alpha$) of 0.05 and a statistical power of 0.80, suitable for repeated measures ANOVA (Jekauc et al., 2021). To account for an expected dropout rate of approximately 30%, the target recruitment was set at 1,150 participants. However, due to a lower-than-anticipated dropout rate, 1,056 orthopedic rehabilitation patients were enrolled at baseline.

A total of 1,056 participants were recruited in 2020-2022 at several rehabilitation clinics, including those within the German Knappschafts-Kliniken network located in Badenweiler, Marquartstein, Bad Soden-Salmünster, Bad Homburg, and Warmbad. Participants were stratified into three groups: 405 in the digital rehabilitation group (digIRENA), 352 in the conventional rehabilitation group (IRENA), and 299 in the control group. Group allocation was partially randomized, taking into account participant preferences and availability of rehabilitation options. All participants were initially offered enrollment in the conventional IRENA program, which is the standard aftercare program in Germany. Participants who accepted this offer formed the non-randomized IRENA group. Those who declined participation in IRENA due to logistical or personal reasons were subsequently randomized in a 1:1 ratio to either the digIRENA group or the control group. However, a significant proportion of participants refused to participate in the study when they were allocated to the control group, resulting in smaller group sizes for the control group compared to the digIRENA group. This discrepancy highlights the challenge of maintaining balanced group sizes in a real-world setting where patient preferences play a critical role. Despite these differences, randomization ensured comparability between the digIRENA and control groups in terms of baseline characteristics. Demographically, the majority of participants were male (67.3%), with an average age of 54.18 years. Retention rates across the study were robust, with 907 participants completing the second time point (T1) and 853 completing the final time point (T3).

## Interventions

### Traditional IRENA Aftercare

The traditional IRENA (Intensified Rehabilitation Aftercare) program is a structured multimodal aftercare intervention designed to support patients' transition back into everyday life and work following orthopedic rehabilitation. It provides up to 24 sessions over a period of 12 months, with each session lasting between 90 and 120 minutes, depending on patient needs and rehabilitation goals. The program emphasizes maintaining and reinforcing the gains made during primary rehabilitation, focusing on enhancing physical, cognitive, and psychological well-being. Participants in the IRENA group were asked at follow-up time points (T1, T2, and T3) whether they had started the aftercare sessions, the number of weeks in which they participated in at least one session, and the average duration of their weekly participation. These self-reported data were used to estimate adherence to the program.

IRENA includes various therapeutic elements such as physical therapy, psychoeducation, and training sessions aimed at improving overall functional capacity, particularly in the musculoskeletal system (DRV, 2021). The program is interdisciplinary, involving physiotherapists, psychologists, and social workers to deliver a comprehensive rehabilitation approach. Sessions typically take place in a group setting, which allows participants to engage in supervised activities such as strength training, endurance exercises, and coordination activities. Additionally, psychoeducational components address stress management, coping strategies, and the integration of rehabilitation success into daily life (DRV, 2021).

### Digital IRENA (digIRENA)

The digital IRENA (digIRENA) program is a telerehabilitation aftercare intervention delivered through a digital platform, Caspar Health. The intervention is designed to provide flexible, remote access to rehabilitation services, allowing participants to continue their recovery independently while still receiving structured guidance and support. The app offers tailored rehabilitation programs based on individual patient needs, similar to the traditional IRENA, but in a more accessible and user-driven format. The digIRENA platform delivers a combination of video-based exercises, educational content, and interactive features to facilitate the rehabilitation process. Patients can access personalized exercise programs, which include strength training, coordination exercises, and mobility activities, all of which are guided by video tutorials. These exercise modules are customized to each patient's condition and rehabilitation goals and are updated periodically based on patient progress.

A key component of digIRENA is the remote supervision feature. Patients can submit progress reports, complete feedback forms, and communicate with their rehabilitation team via the app. Healthcare professionals, including physiotherapists and rehabilitation specialists, monitor the patient's progress remotely and provide feedback or modifications to the exercise programs as needed. This interaction ensures that the rehabilitation process remains aligned with the patient's recovery goals, even in a digital environment. In addition to the physical exercise components, psychoeducational content is delivered through the app to address mental health aspects such as stress management, motivation, and coping strategies. Patients receive regular notifications and reminders to keep them engaged and help maintain adherence to the rehabilitation plan. The app also incorporates tools for self-monitoring, enabling participants to track their progress over time and assess their work ability improvements. Adherence in the digIRENA group was tracked through self-reported measures, including the number of weeks participants engaged with the program and the average weekly time spent on exercises and activities within the platform. These measures were captured at T1, T2, and T3 to calculate overall adherence.

### Control Group

In the control group, no structured aftercare intervention was offered. Participants were encouraged to engage in self-directed physical activity, but adherence to this recommendation was not formally tracked. Unlike those in the IRENA or digIRENA groups, control group members were encouraged to engage in self-directed physical activity but were not provided with formal support, guidance, or monitoring from rehabilitation professionals. This allowed for a comparison between structured rehabilitation aftercare and no formalized follow-up, helping to assess the effectiveness of both digital and conventional aftercare interventions on work ability.

## Measures

### Work Ability

The primary outcome of the study was work ability, assessed using the short version of the Work Ability Index (WAI) developed by Hasselhorn and Freude (Hasselhorn & Freude, 2007). The WAI is a validated tool that measures work ability including seven aspects: (I) current work ability compared to lifetime best, (II) work ability in relation to job demands, (III) number of physician-diagnosed diseases, (IV) self-assessed impairment of work ability due to diseases, (V) sick leave days in the past 12 months, (VI) self-perceived ability to work over the next two years, and (VII) mental performance reserve. The WAI consists of 10 items with both categorical and continuous response formats, generating a total score that ranges from 7 to 49. Higher scores indicate better work ability. The WAI has demonstrated good reliability, with a Cronbach's alpha of 0.78 (Martus et al., 2011), and its validity is supported by its predictive ability regarding early career exit and the duration of work disability (Burdorf et al., 2005; Salonen et al., 2003). In addition to the WAI, demographic data such as age, gender, and employment status were collected through the questionnaire. The employment status variable was categorized into three groups: full-time, part-time, and unemployed. These demographic variables were used to control for potential confounding effects when analyzing the impact of the interventions on work ability.

### Adherence

Adherence to the rehabilitation aftercare programs was assessed through self-reported measures collected at three follow-up time points (T1, T2, T3). Participants in both the digIRENA and IRENA groups were asked whether they had started their respective aftercare programs. For those who had initiated participation, additional information was

collected on the frequency of participation (number of weeks in which at least one session was attended) and the average weekly duration of participation (in minutes). These data allowed for the calculation of the total training time for each participant at each time point.

## Statistical Analyses

Prior to conducting statistical analyses, the dataset underwent preliminary data processing. Missing data were analyzed separately for each measurement point using Little's MCAR test to determine if the data were missing completely at random (Little, 1988). Missing values at the item level were handled through an Expectation Maximization algorithm, which iteratively calculates maximum likelihood estimates. Post-imputation, imputed values were rounded to the nearest integer. If fewer than 50% of the required data for a specific questionnaire were available, missing data were not imputed, and the scale score was recorded as missing, thereby excluding the data from further analysis.

Descriptive statistics were computed for the variables gender, age, nationality, and employment status. Differences between the IRENA and digIRENA groups in terms of gender, nationality, and employment status were assessed using chi-squared goodness-of-fit tests, while one-way ANOVA was employed to analyze differences in age between the groups. Additionally, dropout analyses were conducted to determine whether the missingness was random or systematic using Little's MCAR test (Little, 1988). Although the IRENA group was not randomized, it was included in the analysis to serve as a comparator group, reflecting real-world practices where patients often choose conventional rehabilitation. The inclusion of this group provides a context for evaluating the effectiveness of the digIRENA intervention and allows comparisons with the standard of care. To account for potential biases introduced by the non-randomized nature of the IRENA group, baseline characteristics were compared across groups, and differences were controlled for in the analyses where applicable. This approach aimed to reduce the influence of group imbalances on the observed intervention effects.

Adherence to the rehabilitation aftercare interventions was analyzed descriptively, based on self-reported data collected at T1, T2, and T3. Participants in both the digIRENA and IRENA groups reported whether they had started the aftercare intervention and, if so, provided information on the number of weeks they had participated in at least one session and their average weekly participation time. From these data, the total adherence time in minutes was calculated. Differences in adherence between the digIRENA and IRENA groups were assessed using chi-squared tests for the initiation of aftercare participation and independent samples t-tests for the total adherence time at each measurement point. Effect sizes (Cohen's d and φ) were reported for group comparisons to provide a measure of the magnitude of these differences.

To evaluate changes in work ability over time, repeated measures ANOVA was conducted across the four measurement points (T0, T1, T2, T3). This analysis facilitated the examination of longitudinal trends in work ability and differences between the intervention groups. Mauchly's test was used to assess the assumption of sphericity, and if violations were detected, the Greenhouse-Geisser correction was applied.

A further repeated measures ANCOVA was conducted to assess the interaction between time and group, age, gender, and employment status, following previous findings that suggest age-related differences in responses to digital and conventional rehabilitation approaches. For the analysis of age-related effects, participants were categorized into younger and older age groups using a median split. Mean trajectories of work ability across the four time points were presented graphically with 95% confidence intervals for each group. In cases where significant interactions were identified, additional graphical analyses were provided. The selection of repeated measures ANOVA and ANCOVA as the primary analytical approaches was guided by the longitudinal nature of the data and the research objective of evaluating changes in work ability over time. These methods are well-suited for analyzing within-subject changes and time-dependent interactions while accounting for repeated measures on the same individuals. Repeated measures ANOVA provides a robust framework for assessing group differences over time, while ANCOVA enables the inclusion of covariates to control for baseline differences and examine potential moderators such as age, gender, and employment status. All analyses were performed in SPSS version 28, using an alpha level of 0.05.

# Results

## Sample Description and Dropout Analysis

At baseline (T0), a total of 1,056 participants were enrolled in the study, with 405 participants assigned to the digIRENA group, 352 to the IRENA group, and 299 to the control group (see Table 12). The overall sample was predominantly male, comprising 67.3% of the total population, with a similar proportion of males in the digIRENA (64.2%) and IRENA (65.6%) groups. However, the proportion of male participants was significantly higher in the control group (73.6%) compared to the other two groups, as indicated by a chi-square test ($\chi^2 = 7.5$, $df = 2$, $p = 0.024$).

Table 12: Sample Characteristics at T0.

| | digIRENA | IRENA | Control | overall |
|---|---|---|---|---|
| | 405 (100 %) | 352 (100 %) | 299 (100 %) | 1056 (100 %) |
| Gender | | | | |
| male | 260 (64.2 %) | 231 (65.6 %) | 220 (73.6 %) | *711* (67.3 %) |
| female | 145 (35.8 %) | 120 (34.1 %) | 79 (26.4 %) | *344* (32.6 %) |
| divers | 0 | 1 (0.3 %) | 0 | *1* (0.1 %) |
| missing | 0 | 0 | 0 | *0* |
| Age | | | | |
| Mean | 53.00 | 54.21 | 55.74 | *54.18* |
| Standard deviation | 8.75 | 7.90 | 6.30 | *7.91* |
| n | 405 | 351 | 299 | *1055* |
| missing | 0 | 1 | 0 | *1* |
| Nationality | | | | |
| German | 398 (98.3 %) | 339 (96.3 %) | 294 (98.3 %) | *1031* (97.6 %) |
| Non-German | 7 (1.7 %) | 11 (3.1 %) | 4 (1.3 %) | *22* (2.1 %) |
| missing | 0 | 2 (0.6 %) | 1 (0.3 %) | *3* (0.3 %) |
| Employment Status | | | | |
| Full-Time (> 34 h) | 318 (78.5 %) | 265 (75.3 %) | 238 (79.6 %) | *821* (77.7 %) |
| Part-Time (< 34 h) | 53 (13.1 %) | 45 (12.8 %) | 29 (9.7 %) | *127* (12.0 %) |
| Education | 2 (0.5 %) | 2 (0.6 %) | 0 | *4* (0.4 %) |
| Unemployed | 32 (7.9 %) | 37 (10.5 %) | 32 (10.7 %) | *101* (9.6 %) |
| missing | 0 | 3 (0.9 %) | 0 | *3* (0.3 %) |

The mean age of participants significantly differed between the groups ($F = 10.5$, $df_1 = 2$, $df_2 = 1052$, $p < 0.01$, $\eta^2 = 0.020$). Participants in the control group were on average slightly older ($M = 55.74$, $SD = 6.30$) compared to the IRENA group ($M = 54.21$, $SD = 7.90$) and the digIRENA group ($M = 53.00$, $SD = 8.75$). Bonferroni post-hoc analysis showed that the mean age in the control group was significantly higher than in both the IRENA and digIRENA groups. Most participants were of German nationality (97.6%). There were no significant differences in nationality distribution between the groups ($\chi^2 = 3.0$, $df = 2$, $p = 0.224$). Regarding employment status, 77.7% of participants were employed full-time, 12.0% part-time, and 9.6% were unemployed. No significant differences were observed between the groups in terms of employment status ($\chi^2 = 4.2$, $df = 4$, $p = 0.374$).

Dropout rates were assessed across the four measurement time points (T0, T1, T2, and T3). At baseline, 33 participants (3.13% of the total sample) had missing data for the WAI, affecting a total of 73 data points (0.69%) across 10 of the 24 items. Little's MCAR test indicated that the missing data at T0 were completely random ($\chi^2 = 160.4$; $df = 144$; $p = 0.165$). At T1, 22 participants (2.43% of the remaining sample of 907) had missing data for the WAI, affecting 41 values (0.45%) across the same 10 items. The MCAR test again suggested that the missing data were random ($\chi^2 = 101.6$; $df = 102$; $p = 0.491$). At T2, 15 participants (1.73% of the 866 remaining participants) had missing WAI data, impacting 52 values (0.60%). Little's test indicated no systematic pattern in the missing data ($\chi^2 = 65.4$; $df = 65$; $p = 0.464$). By T3, 19 participants (2.23% of the 853 remaining participants) had missing data, with 30 values (0.35%) missing across 10 WAI items. As with the previous time points, the missing data were deemed to be completely random ($\chi^2 = 93.0$; $df = 93$; $p = 0.481$). These analyses suggest that no significant patterns of systematic missingness were observed.

## Adherence

At T1, 98.9% of participants in the digIRENA group reported initiating the program compared to 77.5% in the IRENA group, with a significant difference in proportions ($\chi^2 = 78.3$; $df = 1$; $p < 0.01$; $\varphi = 0.35$). At T2, participation rates remained higher in the digIRENA group (98.9%) than in the IRENA group (86.6%) ($\chi^2 = 38.6$; $df = 1$; $p < 0.01$; $\varphi = 0.25$). Similarly, at T3, 99.5% of the digIRENA participants had engaged with the program, compared to 88% in the IRENA group, demonstrating a consistent advantage for digIRENA across all time points ($\chi^2 = 38.1$; $df = 1$; $p < 0.01$; $\varphi = 0.25$).

The total reported training time, calculated in minutes, was significantly higher in the digIRENA group compared to the IRENA group at all time points. At T1, the average training time in the digIRENA group was 982.8 minutes ($SD = 562.5$) versus 789.1 minutes ($SD = 676.5$) in the IRENA group ($t = 3.8$; $df = 522.2$; $p < 0.01$; $d = 0.32$). At T2, participants in the digIRENA group reported an average of 1,551.8 minutes ($SD = 636.4$) compared to 1,314.7 minutes ($SD = 798.5$) in the IRENA group ($t = 3.8$; $df = 447.5$; $p < 0.01$; $d = 0.33$). By T3, the average training time in the digIRENA group further increased to 1,836.2 minutes ($SD = 545.8$), significantly exceeding the IRENA group's 1,491.9 minutes ($SD = 825.8$) ($t = 5.1$; $df = 366.8$; $p < 0.01$; $d = 0.50$).

## Work Ability

The descriptive statistics for the WAI across the four measurement points (T0, T1, T2, T3) are presented in Table 13. At baseline (T0), mean WAI scores were similar among the three groups with no significant differences between the three groups ($F = 2.2$; $df_1 = 2$; $df_2 = 1048$; $p = 0.11$).

Table 13: Descriptive Statistics for WAI.

| Time | digIRENA | | | IRENA | | | Control | | |
|---|---|---|---|---|---|---|---|---|---|
| | n | Mean | SD | n | Mean | SD | n | Mean | SD |
| T0 | 319 | 27.94 | 7.63 | 249 | 27.19 | 7.79 | 230 | 28.39 | 7.51 |
| T1 | 319 | 29.95 | 7.86 | 249 | 28.63 | 9.00 | 230 | 29.51 | 8.30 |
| T2 | 319 | 30.58 | 8.18 | 249 | 28.87 | 9.10 | 230 | 29.50 | 8.60 |
| T3 | 319 | 30.63 | 8.57 | 249 | 28.91 | 9.36 | 230 | 29.60 | 9.04 |

Note: *n* = number of participants; *SD* = standard deviation

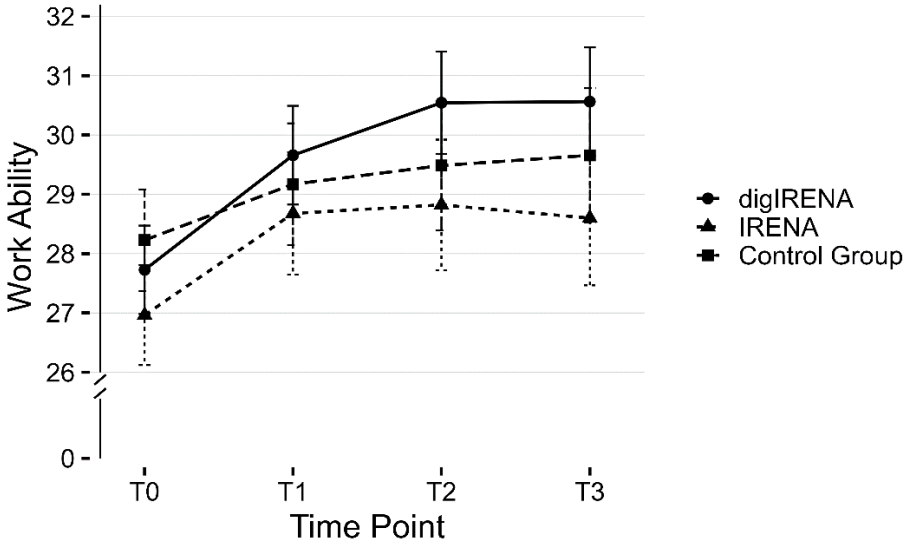
The results of the analysis of variance with repeated measurement are presented in Table 14 and indicate that both time ($F = 37.6$, $df_1 = 2.7$, $df_2 = 2113.4$, $p < 0.01$, $\eta^2 = 0.045$) and the interaction between time and group ($F = 2.2$, $df_1 = 5.3$, $df_2 = 2113.4$, $p < 0.01$, $\eta^2 = 0.006$) had significant effects on work ability. The significant effect of time suggests that all three groups showed significant improvements in work ability over time. Further analyses revealed both a linear ($F = 58.4$, $df_1 = 1$, $df_2 = 18642.6$, $p < 0.01$, $\eta^2 = 0.068$) and a quadratic ($F = 28.7$, $df_1 = 1$, $df_2 = 11552.4$, $p < 0.01$, $\eta^2 = 0.035$) trend in the development of work ability over time. The increase in work ability from T0 to T1 was relatively steep for all groups, after which the rate of improvement plateaued between T1 and T2 (see Figure 14). Between T2 and T3, the mean work ability scores remained stable across all groups. The significant interaction between time and group suggests that the digIRENA group showed a notably steeper improvement in work ability compared to the IRENA and control groups, particularly from T0 to T1 and T1 to T2 (see Figure 14). This interaction exhibited a significant linear trend over time ($F = 3.9$, $df_1 = 2$, $df_2 = 18642.6$, $p = 0.02$, $\eta^2 = 0.010$), indicating that the rate of improvement differed between the groups across the study period.

Table 14: Repeated measurement ANOVA with time and group as independent variables.

| Variable | SS | df | MSS | F | p | partial $\eta^2$ |
|---|---|---|---|---|---|---|
| Time | 1825.1 | 2.7 | 686.5 | 37.6 | <0.001 | 0.045 |
| Time*Group | 214.0 | 5.3 | 40.3 | 2.2 | 0.047 | 0.006 |
| Error | 38564.2 | 2113.4 | 18.2 | | | |

Note: SS = sum of squares; df = degrees of freedom; MSS = mean sum of squares

Figure 14: Development of WAI for digIRENA, IRENA, and control groups from T0 to T3.




Analyses of Variance with Age, Gender, and Employment Status

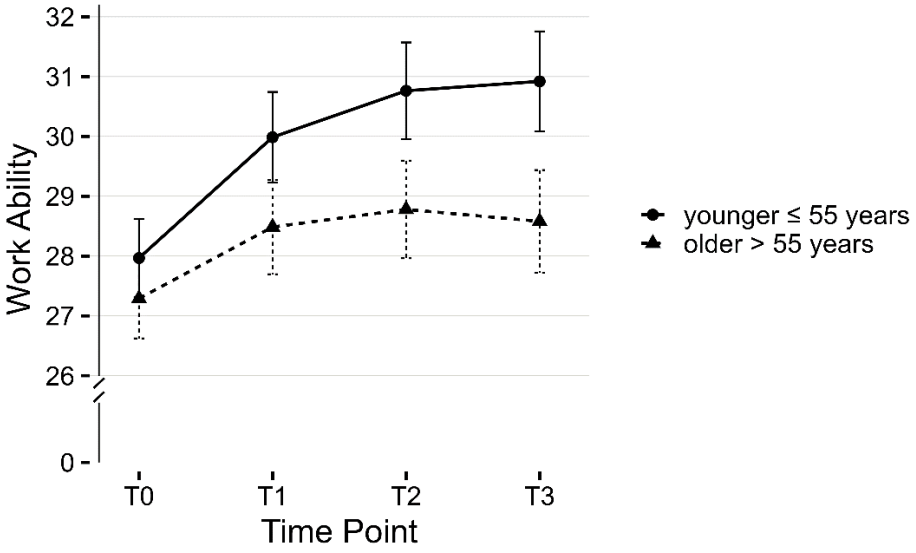
In a subsequent analysis, gender and employment status were included as factors, while age was treated as a covariate in the repeated-measures ANOVA. The results are presented in Table 15. The effect of time remained significant ($F = 26.7$, $df1 = 2.7$, $df2 = 2092.8$, $p < 0.001$, $\eta^2 = 0.033$), while the interaction between time and group ($F = 0.7$, $df1 = 5.4$, $df2 = 2092.8$, $p = 0.608$, $\eta^2 = 0.002$) was no longer significant. However, significant interactions were observed between time and age ($F = 16.8$, $df1 = 2.7$, $df2 = 2092.8$, $p < 0.001$, $\eta^2 = 0.021$) and between time and employment status ($F = 4.3$, $df1 = 5.4$, $df2 = 2092.8$, $p < 0.001$, $\eta^2 = 0.011$), indicating that these factors significantly influenced the development of work ability over the four measurement points.

Table 15: ANCOVA with repeated measurement including time, age, gender, group, and employment status as independent variables.

| Variable | SS | df | MSQ | F | p | partial $\eta^2$ |
|---|---|---|---|---|---|---|
| time | 1248,9 | 2,7 | 461,3 | 26,7 | <,001 | 0,033 |
| time*age | 787,0 | 2,7 | 290,7 | 16,8 | <,001 | 0,021 |
| time*group | 68,8 | 5,4 | 12,7 | 0,7 | 0,608 | 0,002 |
| time*gender | 1,7 | 2,7 | 0,6 | 0,0 | 0,986 | 0 |
| time*employment | 405,6 | 5,4 | 74,9 | 4,3 | <,001 | 0,011 |
| time*group*gender | 52,9 | 5,4 | 9,8 | 0,6 | 0,741 | 0,001 |
| time*group*employment | 256,2 | 10,8 | 23,7 | 1,4 | 0,183 | 0,007 |
| time*gender*employment | 105,4 | 5,4 | 19,5 | 1,1 | 0,345 | 0,003 |
| time*group*gender*employment | 86,3 | 10,8 | 8,0 | 0,5 | 0,926 | 0,002 |
| Error | 36211,1 | 2092,8 | 17,3 | | | |

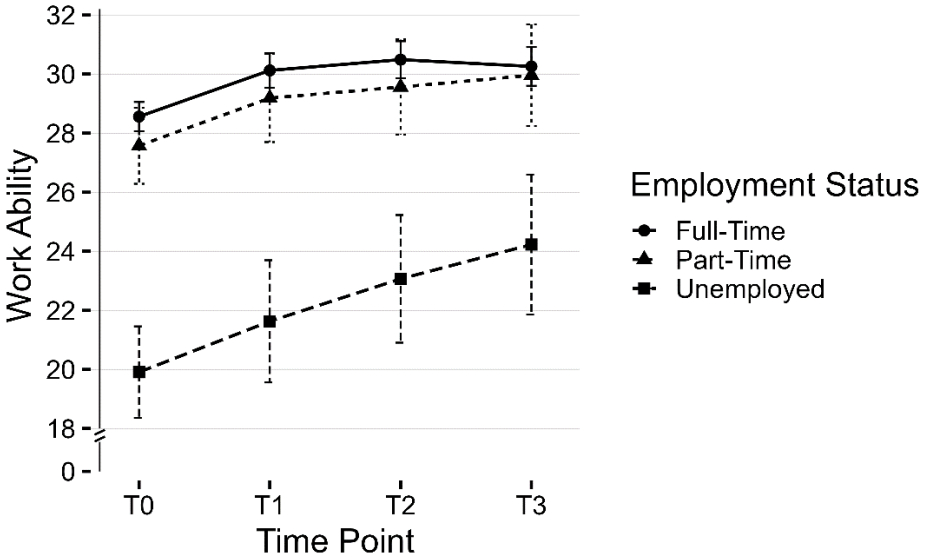
Note: SS = sum of squares; df = degrees of freedom; MSS = mean sum of squares

Figure 15: Development of WAI for younger (≤ 55 years) and older (> 55 years) participants from T0 to T3.




In a further analysis, age was dichotomized using a median split, and the repeated-measures ANOVA was recalculated. The results indicated that younger participants (aged 55 years and younger) benefited more significantly from the rehabilitation intervention compared to older participants (see Figure 15). Additionally, the interaction between time and employment status revealed that non-working individuals had a significantly lower baseline level of work ability compared to those employed full-time or part-time (see Figure 16). However, the unemployed group exhibited a steeper increase in work ability over the four measurement points, compared to the other two employment groups.

Figure 16: Development WAI based on employment status from T0 to T3.



# Discussion

The primary objective of this study was to compare the effectiveness of digital rehabilitation aftercare with traditional IRENA and a control group in improving work ability among orthopedic patients. The results revealed significant improvements in work ability over time across all three groups. Notably, the digIRENA group exhibited the most substantial and rapid improvement, particularly between the baseline and the first follow-up. While all groups showed a positive trend in work ability, the digIRENA group consistently outperformed both the traditional IRENA and control groups. Additionally, age and employment status significantly influenced work ability outcomes, with younger participants and non-working individuals benefiting the most from the rehabilitation interventions.

These findings should also be interpreted in light of the potential influence of baseline group differences, as the semi-randomized allocation process may not have fully mitigated pre-existing disparities between groups. Although key demographic variables such as age, gender, and employment status were included as covariates in the analyses, other unmeasured factors – such as socioeconomic background or prior rehabilitation history – may have contributed to the observed outcomes. The absence of comprehensive baseline data limits the ability to definitively attribute the intervention effects solely to the rehabilitation programs. This limitation underscores the need for future studies to adopt more rigorous designs, including fully randomized controlled trials or statistical techniques like propensity score matching, to better address potential confounding effects and enhance causal inferences regarding the effectiveness of digital rehabilitation interventions.

The results of this study demonstrate a significant time effect, accounting for 4.5% of the within-person variance in work ability. Both a linear and quadratic trend were observed over time. The linear trend indicates that all three groups experienced significant improvements in work ability during the 12-week period following discharge from orthopedic rehabilitation. This finding aligns with previous studies, which have consistently shown that structured rehabilitation interventions lead to improvements in work ability and overall functional capacity in orthopedic patients (Kuoppala & Lamminpaa, 2008; Oakman et al., 2018). These increases in work ability suggest that orthopedic rehabilitation, regardless of the mode of delivery, is generally effective in helping patients recover their capacity to work.

The quadratic trend observed in the data indicates that the improvement in work ability began to stabilize 12 weeks post-rehabilitation, with this stabilization continuing through the four-month follow-up period. This plateau suggests that the positive effects of rehabilitation are maintained over time, reflecting the long-term benefits of aftercare interventions. These findings are consistent with previous research, which has shown that improvements in work ability tend to plateau after the initial phase of recovery, but can be sustained over several months with proper follow-up (Wallstedt-Paulsson & Eklund, 2008). The sustainability of these effects is critical for preventing long-term work disability and early retirement, as supported by studies highlighting the long-term impact of rehabilitation on reducing sickness absence and improving workforce participation (Kuoppala & Lamminpaa, 2008; Madsen, 2020).

The significant interaction between time and group indicates that the effect of digital rehabilitation aftercare (digIRENA) is slightly stronger than that of the traditional IRENA and control groups. Specifically, the digIRENA group demonstrated the steepest increase in work ability during the first 12 weeks of the follow-up period, reflecting the early effectiveness of the digital intervention. Additionally, while the effects in the IRENA and control groups stabilized in the second half of the aftercare period, the digIRENA group continued to show improvements in work ability. This sustained improvement highlights the potential of digital aftercare interventions in promoting long-term gains in work ability.

This study highlights the critical role of adherence in maximizing the benefits of rehabilitation interventions. The self-reported data on adherence revealed that participants in the digIRENA group were more likely to initiate and sustain their engagement with aftercare programs compared to the traditional IRENA group. This difference in adherence may explain the superior outcomes observed in the digIRENA group, as consistent participation is essential for achieving optimal rehabilitation outcomes. The flexibility and accessibility of digital platforms likely contributed to higher adherence rates, allowing participants to integrate rehabilitation exercises into their daily routines more effectively (Lang et al., 2022). However, future research should explore objective measures of adherence, such as platform usage logs, to validate self-reported data and provide deeper insights into the mechanisms driving these differences.

These findings are consistent with previous studies that have reported benefits of digital rehabilitation platforms in maintaining patient engagement and adherence to rehabilitation protocols, particularly when compared to traditional rehabilitation (Jang et al., 2023). The continued improvement observed in the digIRENA group may be attributed to

the flexibility and accessibility of digital interventions, which allow patients to integrate rehabilitation exercises into their daily lives more easily. Similar results were found in a study by Martinez-Rico et al. (Martinez-Rico et al., 2018), where telerehabilitation intervention led to sustained functional gains over time, surpassing traditional rehabilitation program. This suggests that digital rehabilitation platforms like digIRENA may play a key role in enhancing work ability, particularly for patients who face logistical barriers to accessing conventional rehabilitation services (Fortney et al., 2011).

When age, gender, and employment status were included in the ANOVA, the interaction between time and group was no longer significant, suggesting that sociodemographic variables may have moderated this effect. Notably, the interaction between time and age emerged as a significant factor, indicating that younger participants benefited more from the rehabilitation interventions than their older counterparts. In younger participants, the increase in work ability was continuous and sustained, even after the formal aftercare period. In contrast, for older participants, improvements were only evident during the first 12 weeks post-rehabilitation, with little or no further gains afterward.

This age-related difference in response to rehabilitation may be due to several factors. Biological aging processes, such as slower recovery rates, reduced physical resilience, and the presence of comorbidities, could explain the diminished gains observed in older individuals. Research has shown that as people age, physical recovery from musculoskeletal injuries or surgeries tends to be slower (Talwar et al., 2024), which could limit the overall effectiveness of rehabilitation programs. Another possible explanation is related to digital literacy. Younger participants may have been more comfortable using the digital platform provided by the digIRENA intervention, which could have enhanced their engagement and adherence to the rehabilitation program. Studies have shown that digital literacy can influence the effectiveness of online health interventions (Arias López et al., 2023; Campanozzi et al., 2023), with younger individuals generally being more adept at navigating and utilizing digital tools (Schreurs et al., 2017). This may explain why the younger participants in our study showed more sustained improvements, particularly in the digital aftercare group. Similar findings were reported by Schmidt et al. (Schmidt et al., 2023), who noted that younger individuals tend to benefit more from digital prevention interventions.

The interaction between time and employment status had a significant effect on the development of work ability. Participants who were not employed at baseline had significantly lower initial levels of work ability compared to those who were employed either full-time or part-time. However, the non-employed group showed the steepest increase in work ability over time. This finding aligns with previous research suggesting that individuals with lower initial functional capacity often experience the greatest relative gains from structured rehabilitation programs (Eng et al., 2003). This suggests that individuals not currently in the workforce, possibly due to more severe health impairments, benefited the most from rehabilitation and aftercare interventions. One potential explanation for this finding is that non-employed individuals, likely facing greater functional limitations at baseline, had more room for improvement. The low initial levels of work ability could be attributed to more severe health problems, longer periods of inactivity, or other challenges associated with their conditions. Previous research has shown that individuals with more severe health issues often exhibit more pronounced physical and functional deficits but also tend to achieve greater relative gains from rehabilitation interventions (Jørgensen et al., 2000). The steep improvement in work ability in this group suggests that rehabilitation programs are particularly effective for those starting from a lower baseline, offering substantial potential to increase their self-acceptance, acceptance by others, physical capacity, psychological resources and capacity to balance engagement (Andersen et al., 2022).

Additionally, employment status may influence rehabilitation outcomes by shaping the time and resources participants can allocate to their recovery. Employed individuals may face competing priorities and time constraints, which could limit their adherence to aftercare interventions. Conversely, non-employed participants may have more flexibility to engage fully with rehabilitation programs, which could explain their steeper improvement trajectory (39). However, research specifically addressing the role of employment status in rehabilitation outcomes is limited, and further studies are needed to explore how these factors interact to influence long-term work ability. Futhermore, the current findings highlight the need for more research on the relationship between employment status and rehabilitation outcomes, particularly in the context of digital aftercare interventions. While previous studies have examined general predictors of rehabilitation success (McKechnie et al., 2019; van der Laag et al., 2021), the specific mechanisms through which employment status affects work ability remain underexplored. By demonstrating that non-employed individuals can achieve significant improvements in work ability, this study contributes novel insights to the field and underscores the importance of tailoring interventions to the needs of different employment groups.

## Implications for Practice

The findings of this study have several important implications for clinical practice and rehabilitation programs. First, the demonstrated effectiveness of digital rehabilitation aftercare highlights the potential of telerehabilitation platforms to provide flexible and accessible alternatives to traditional in-person aftercare. Given the sustained improvements in work ability observed in the digIRENA group, digital interventions could be integrated into routine care, especially for patients facing geographical, logistical, or time constraints. The study also underscores the importance of tailoring rehabilitation programs to specific patient populations, particularly in terms of age and employment status. Younger patients showed more consistent improvement in work ability, suggesting that digital interventions may be particularly well-suited for this demographic, likely due to their higher digital literacy and comfort with technology. Conversely, older patients may require additional support, such as hybrid models combining in-person and digital care, to achieve similar outcomes. Rehabilitation programs should consider offering more personalized interventions for older adults to account for their slower recovery rates and potential challenges in engaging with digital platforms.

The findings also demonstrate that rehabilitation and aftercare interventions can have a substantial impact on improving work ability for unemployed individuals. These individuals, who may begin rehabilitation with lower functional levels, benefit significantly from structured rehabilitation programs. The significant improvements observed in non-employed individuals suggest that rehabilitation programs could serve as a platform for enhancing not only physical recovery but also employability. Future interventions might benefit from incorporating job readiness training or vocational support to complement physical rehabilitation, thereby addressing the multifaceted challenges faced by non-employed individuals. Finally, the study reinforces the importance of long-term follow-up care. The sustained improvements in work ability seen in the digital aftercare group indicate that ongoing support beyond the initial rehabilitation period is crucial for maintaining functional gains. Healthcare providers should consider implementing long-term digital or hybrid follow-up care models to support patients' work ability and prevent relapses or declines in functional capacity.

## Limitations

Several limitations of this study should be acknowledged. First, the study relied on self-reported measures of work ability using the WAI, which may introduce reporting bias. Participants' subjective perceptions of their work ability might not fully capture objective improvements in physical or functional capacity. Future studies would benefit from incorporating objective measures, such as functional tests or workplace performance evaluations, to provide a more comprehensive assessment of rehabilitation outcomes. Second, while the study sample was large and diverse, the majority of participants were male (67.3%), limiting the generalizability of the findings to other populations, particularly women. Comprehensive national statistics detailing the gender distribution within orthopedic rehabilitation in Germany are not available, making it unclear whether this gender proportion is representative of the broader orthopedic rehabilitation population. However, it is possible that the recruitment strategy or the nature of orthopedic rehabilitation referrals may have contributed to the overrepresentation of male participants.

Third, the allocation process introduced potential limitations. The IRENA group was non-randomized, as all participants were initially offered this standard aftercare program, and those who accepted were assigned to this group. This lack of randomization may limit direct comparability between the IRENA group and the other groups, which were assigned through a randomization process. Additionally, a significant proportion of participants declined to participate in the study when allocated to the control group, leading to a smaller sample size for this group. This high drop-out rate in the control group could have introduced bias and reduced the statistical power to detect differences between the groups. Future studies should consider strategies to enhance participant retention, particularly in control groups, to ensure balanced and robust comparisons.

Forth, adherence to the aftercare interventions was assessed through self-reported data, which may be subject to recall bias or social desirability bias. Objective measures of adherence, such as digital platform usage logs or attendance records for in-person sessions, were not available. Additionally, adherence to self-directed physical activity in the control group was not formally monitored, which limits the ability to account for potential contamination effects.

Fifth, another limitation of this study is the potential influence of observed and unobserved group differences. While demographic variables such as age, gender, and employment status were included as covariates in the analysis to mitigate these effects, the naturalistic design of the study means that additional factors – such as baseline health status, socioeconomic background, or prior rehabilitation history – may have contributed to the observed outcomes. The lack

of comprehensive baseline data limits the ability to fully disentangle the effects of the interventions from pre-existing differences between groups. Future research should aim to incorporate a wider range of baseline variables and consider advanced statistical methods, such as propensity score matching or sensitivity analyses, to further address these concerns.

Lastly, the study was conducted within the German healthcare system, which may limit the external validity of the findings to other healthcare settings or countries with different rehabilitation practices or healthcare structures. Moreover, the follow-up period of four months may not have been sufficient to capture the long-term sustainability of the improvements in work ability. Future studies should consider extending the follow-up period to assess the long-term effects of rehabilitation interventions on work ability.

## Future Research Directions

Future research should focus on exploring the long-term sustainability of improvements in work ability following rehabilitation, particularly extending the follow-up period beyond four months to assess whether gains are maintained over several years. Additionally, studies should investigate the role of adherence and engagement with digital platforms like digIRENA to better understand how these factors influence the effectiveness of digital rehabilitation interventions. Future research should emphasize the role of health behavior maintenance in the post-rehabilitation phase. While structured aftercare interventions like digIRENA have proven effective in the short term, the long-term goal must be to encourage participants to engage in independent, self-initiated exercise and other health-promoting behaviors after the completion of formal rehabilitation programs.

Moreover, investigating the applicability of these findings across different healthcare systems and cultural contexts would provide valuable insights into the generalizability of digital rehabilitation interventions in diverse populations. Finally, future studies should explore hybrid models of rehabilitation that combine digital and in-person components, particularly for older adults or those less comfortable with technology, to optimize patient outcomes across varying demographic groups.

## Conclusion

This study demonstrates that both digital and traditional rehabilitation aftercare programs significantly improve work ability among orthopedic patients While the digital intervention (digIRENA) showed the greatest overall gains in observed values, it is important to interpret these findings with caution due to the limitations of the study design. The semi-randomized allocation process and observed baseline differences between groups introduce potential biases, and the lack of comprehensive baseline data further complicates definitive conclusions about the causal effectiveness of the interventions. Additionally, the interaction effects between time and sociodemographic variables such as age, gender, and employment status highlight the importance of considering individual characteristics when evaluating intervention outcomes.

The findings nonetheless underscore the potential of digital platforms to provide flexible and accessible rehabilitation solutions, particularly for patients who face logistical challenges in accessing traditional care. These platforms may be especially beneficial for younger individuals and those not currently employed, as these groups demonstrated the most substantial improvements. However, more rigorous research is needed to validate these results and to disentangle the effects of the interventions from confounding factors. Future studies should employ fully randomized controlled designs or advanced statistical methods, such as propensity score matching, to mitigate potential biases and strengthen causal inferences. Long-term evaluations that include objective measures of work ability, adherence, and health behaviors will also be critical to understanding the sustained impact of digital rehabilitation programs.

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# Chapter V – General Discussion

## Discussion of the Findings

The overarching aim of this dissertation was to empirically investigate the comparative effectiveness of digital and conventional formats in prevention and rehabilitation aftercare, with a particular focus on work ability, physical health, and mental health. Against the backdrop of demographic change and the strategic mission of the German Pension Insurance to preserve and restore employability, this research program examined whether digital programs can constitute a viable and sustainable alternative to conventional services in the German rehabilitation and prevention system.

The dissertation addressed this overarching aim through three empirical studies based on two quasi-experimental designs, each focusing on different stages of the prevention and rehabilitation continuum (Fritsch et al., 2021; Jekauc et al., 2021). Study I compared the effectiveness of a digital prevention program with the established RV Fit program among employees with initial health impairments, thereby addressing Research Question I on the role of digital prevention in promoting work ability and health. Study II focused on the impact of digital versus conventional rehabilitation aftercare on physical and mental health in orthopedic patients, directly addressing Research Question II. Study III examined changes in work ability following digital and conventional rehabilitation aftercare, as well as the absence of structured aftercare, thereby answering Research Question III.

Taken together, these studies provide a comprehensive assessment of digital and conventional formats across prevention and rehabilitation aftercare. Each study contributes to understanding the effectiveness, sustainability, and subgroup-specific impact of these interventions. The purpose of the present discussion is to integrate the findings across studies, relate them back to the research questions posed in the General Introduction, and evaluate their theoretical, practical, and methodological implications. Furthermore, this chapter outlines limitations of the research and identifies avenues for future studies, before concluding with a synthesis of the dissertation's contributions to science, practice, and policy.

### Discussion of Research Question I: Digital vs. Conventional Prevention

The first research question of this dissertation examined the extent to which digital prevention programs improve physical and mental health and work ability compared to conventional prevention programs among employees with initial health impairments. The empirical findings presented in Chapter II demonstrated that both the digital program and the conventional RV Fit program led to improvements in work ability and mental health, whereas no significant effects were observed for physical health. These findings confirm that preventive interventions can be effective in promoting core dimensions of employability, yet they also highlight domain-specific differences in responsiveness.

A central observation was that the effects of prevention were not uniform across age groups. Younger participants benefited more strongly from the digital program, particularly with respect to work ability and mental health, while older participants showed greater improvements in the conventional program. This pattern underscores the importance of considering demographic moderators when evaluating and implementing prevention programs. Theoretically, these results can be interpreted through the lens of technology acceptance and digital literacy. Younger employees are typically more familiar with digital technologies (Urick, 2017), which may facilitate engagement with digital interventions and allow for more effective self-directed learning and practice (Liu et al., 2025). By contrast, older employees may value face-to-face contact, structured guidance, and interpersonal support (Silverstein, 2008), which are more characteristic of conventional prevention settings.

From a theoretical perspective, these findings align with biopsychosocial models of health promotion, which emphasize the interaction between individual characteristics and contextual factors. The age-specific response patterns suggest that the effectiveness of prevention is not determined solely by the intervention format but also by its fit with individual needs, competencies, and preferences. Moreover, the absence of significant effects on physical health may indicate that behavioral and somatic changes require longer periods to manifest (Ju et al., 2022), supporting prior research emphasizing the necessity of long-term interventions to improve physical outcomes.

The practical implications for the German Pension Insurance and rehabilitation providers are twofold. First, prevention programs, both digital and conventional, should be maintained and further developed, as both have demonstrated

potential to improve important outcomes such as work ability and mental health. Second, program allocation and design should increasingly adopt an age-sensitive approach. Hybrid models that combine digital and conventional elements may offer a promising avenue to maximize reach and effectiveness across heterogeneous target groups (cf., Chen et al., 2024; Sandesara et al., 2018). For instance, digital tools could be integrated into conventional programs as supplementary modules for younger participants, while maintaining interpersonal components to accommodate older participants' needs. Moreover, digital health literacy could be systematically fostered prior to the start of digital prevention programs, enabling participants to use digital platforms more effectively and thereby enhancing program outcomes (Corvo et al., 2024). Such educational interventions have been shown to be effective in older adults (Kizilkilic et al., 2025).

Methodologically, the quasi-experimental design of the study represents an important limitation, as participants were not randomized and allocation depended on clinic availability. While this reflects real-world conditions in the German prevention system, it reduces internal validity and limits causal inference. In addition, the relatively high dropout rate and the absence of long-term follow-up assessments restrict conclusions regarding the sustainability of observed improvements. Future studies should employ randomized controlled designs with larger sample sizes, extended follow-up periods, and mixed-method approaches to capture both quantitative effects and qualitative insights into participant experiences.

In summary, Research Question I can be answered by stating that both digital and conventional prevention programs improve work ability and mental health among employees with initial impairments, though no significant effects were found on physical health within the study period. Importantly, age moderates the effectiveness of these interventions, highlighting the necessity of tailoring prevention strategies to demographic subgroups. These findings reinforce the value of offering flexible, hybrid approaches within the DRV framework to meet the diverse needs of the workforce.

## Discussion of Research Question II: Digital vs. Conventional Rehabilitation Aftercare – Health Outcomes in Orthopedic Patients

The second research question of this dissertation examined how digital and conventional rehabilitation aftercare programs compare in terms of sustaining improvements in physical and mental health over time in orthopedic patients. The results of Chapter III indicated that all three groups, including the control group without organized aftercare, showed improvements in both physical and mental health over the observation period. These improvements suggest that rehabilitation itself, combined with natural recovery processes and individual efforts at maintaining activity, contributes to overall health gains. However, the digital aftercare program demonstrated relatively stronger effects, particularly for mental health at the end of the intervention period (T2). Importantly, these gains declined during the follow-up period (T3), highlighting the limited sustainability of intervention effects once structured aftercare ended.

Several moderating effects were observed. First, participants in the digIRENA group demonstrated higher levels of adherence and longer participation durations compared to the IRENA group. This finding underscores the role of digital platforms in lowering barriers to participation by providing greater flexibility and accessibility (Hamilton et al., 2025; Virani, 2025). Second, gender differences emerged: women entered the programs with lower baseline mental health scores but demonstrated steeper improvements over time, eventually reaching levels comparable to men. This pattern indicates that women may derive particular benefit from structured aftercare (Khadanga et al., 2021), although the underlying mechanisms, whether related to psychosocial support, adherence, or other factors, require further investigation.

From a theoretical perspective, these findings reinforce the importance of continuous structured support in sustaining behavior change and health improvements. The observed decline in both physical and mental health aftercare effects once the interventions ended can be interpreted as a manifestation of the well-documented "decay of treatment effects" in rehabilitation research (Annesi, 2016). Without ongoing reinforcement, health-promoting behaviors and motivational gains are difficult to maintain. Digital interventions such as digIRENA appear promising in this regard, as they extend engagement and can be integrated into patients' daily lives with fewer logistical barriers than conventional programs. Yet, the results also reveal that digital programs are not immune to declining effects once structured support ceases. In this context, low-threshold digital offerings may represent a useful adjunct to support the process of behavioral change by providing easily accessible, ongoing reinforcement (Yardley et al., 2016).

The practical implications for rehabilitation practice and health policy are significant. First, the demonstrated benefits of digIRENA support its integration into the standard aftercare repertoire of the German Pension Insurance (Sewöster, 2023). Particularly for patients who face geographical, occupational, or logistical barriers, digital aftercare offers an accessible and effective alternative (Lange-Drenth et al., 2024). Second, the decline of effects after program completion points to the necessity of developing strategies to sustain health gains. These might include booster sessions, step-down interventions, or hybrid models that combine digital flexibility with periodic interpersonal contact (Lai et al., 2019). Third, gender-specific considerations may enhance intervention design, given the stronger relative improvements observed among women (Chui & Gordon, 2025).

Methodologically, the study had several notable strengths. The large sample size and longitudinal design allowed for robust analyses of health trajectories across four time points, capturing both short-term and medium-term changes. The inclusion of both intervention and control groups enhances the interpretability of results and strengthens external validity by reflecting real-world rehabilitation conditions. Nevertheless, limitations must be acknowledged. The semi-randomized design raises the possibility of self-selection bias, particularly since patients could decline IRENA and were then randomized between digIRENA and control. Attrition and reliance on self-report measures (e.g., SF-12 health scales) further limit the precision of conclusions. Additionally, the study was conducted during the COVID-19 pandemic, which may have influenced participation patterns, mental health outcomes, and the relative attractiveness of digital formats.

In summary, Research Question II can be answered by concluding that digital rehabilitation aftercare is at least as effective as conventional IRENA and, in some respects, more effective in improving physical and mental health. However, the beneficial effects of both formats diminish after program completion, underscoring the importance of sustained support mechanisms. The evidence suggests that digital interventions should play a central role in the future of rehabilitation aftercare but need to be complemented by strategies that address long-term adherence and maintenance of health benefits (Rose & Cox, 2023).

## Discussion of Research Question III: Digital vs. Conventional Rehabilitation Aftercare – Work Ability in Orthopedic Patients

The third research question of this dissertation examined whether digital rehabilitation aftercare leads to greater improvements in work ability compared to conventional aftercare or no organized aftercare among orthopedic patients. The results reported in Chapter IV demonstrated that work ability improved significantly across all three groups over time, confirming the general effectiveness of rehabilitation and natural recovery processes. However, the digIRENA group exhibited steeper and more sustained improvements in the early and intermediate phases of follow-up, indicating a relative advantage of the digital format. These advantages diminished when sociodemographic covariates such as age and gender were included in the analysis, suggesting that the effectiveness of digital interventions is moderated by individual characteristics.

The moderating analyses revealed that younger participants benefited more strongly from rehabilitation aftercare, particularly in the digital format. This finding may reflect both biological and psychosocial mechanisms. Younger individuals typically recover more quickly from musculoskeletal impairments and are more likely to possess digital literacy and familiarity with technology-based interventions, thereby enhancing engagement with digital aftercare platforms. In contrast, older participants showed smaller and less sustained gains in work ability, likely due to slower recovery rates, higher comorbidity burdens, and potential difficulties in navigating digital systems. Furthermore, employment status emerged as a significant moderator. Unemployed participants started with lower baseline levels of work ability but showed the steepest relative gains, suggesting that those with the greatest impairments may benefit most from structured aftercare interventions. This aligns with previous evidence indicating that patients with lower initial functional capacity often show the strongest relative improvements during rehabilitation (Minnella et al., 2016).

From a theoretical perspective, these findings underscore the multidimensional nature of work ability, which is shaped not only by physical and mental health but also by demographic and occupational context (Tengland, 2011). Digital rehabilitation formats may be particularly effective in fostering self-initiated exercise, autonomy, and flexible engagement (Schroeer et al., 2021), features that align well with younger and more digitally literate populations. At the same time, the attenuation of group effects after accounting for age and employment status highlights that intervention effectiveness cannot be understood independently of individual characteristics (Schwab et al., 2022). Work ability

should therefore be conceptualized as the result of dynamic interactions between health, personal resources, and occupational demands (McGonagle et al., 2014), which vary across life stages and employment situations (Price, 2015).

The practical implications are clear for both rehabilitation providers and policymakers. The DRV and rehabilitation clinics should consider prioritizing digital aftercare for younger patients and those with flexible or precarious occupational contexts, as these groups appear to benefit most. At the same time, conventional aftercare remains necessary for older patients and those with limited digital literacy, who may require interpersonal support and structured group-based rehabilitation to achieve comparable outcomes. Hybrid approaches, which combine digital flexibility with targeted interpersonal contact, could help optimize outcomes across heterogeneous patient populations (Truntzer & Gorman, 2025). Furthermore, the strong relative gains observed among unemployed participants highlight the potential of aftercare programs to contribute not only to health recovery but also to reintegration into the workforce. Integrating vocational support elements into rehabilitation pathways may further strengthen these effects (Dutta et al., 2008).

In summary, Research Question III can be answered by concluding that digital rehabilitation aftercare is at least as effective, and in some respects superior, to conventional aftercare and no structured aftercare in improving work ability. Its relative advantage is most pronounced in younger and unemployed individuals, suggesting that digital formats may be particularly well suited for subgroups with higher digital literacy and greater potential for functional gains. However, the attenuation of group differences after controlling for sociodemographic variables underscores the necessity of tailoring aftercare interventions to individual characteristics. Together, these findings highlight the value of flexible, differentiated, and hybrid aftercare models within the German rehabilitation system.

# Integration Across Research Questions

The three empirical studies presented in this dissertation provide complementary insights into the comparative effectiveness of digital and conventional prevention and rehabilitation aftercare programs within the German rehabilitation system. By focusing on employees with initial impairments (Study I), orthopedic patients' health outcomes (Study II), and work ability trajectories (Study III), the studies collectively capture different issues of the prevention and rehabilitation continuum. Taken together, several cross-cutting findings emerge.

## Comparative Evidence on Digital versus Conventional Programs

The three studies in this dissertation converge on a central conclusion: digital formats are at least as effective as conventional formats across prevention and rehabilitation aftercare, with indications of superiority for mental health and early gains in work ability, particularly among younger participants. This pattern is consistent with international syntheses in adjacent domains. A meta-analysis of randomized trials comparing electronically delivered and face-to-face cognitive behavioral therapy reported a relatively large advantage of digital delivery for depressive symptom reduction, with parity for quality of life, satisfaction, and dropout, and one trial indicating lower cost for the digital arm (Luo et al., 2020). In addition, a review of interactional processes in remote therapy found no reliable deficits for therapeutic alliance, empathy, disclosure, attentiveness, or participation when sessions are conducted by telephone rather than in person, and documented shorter session lengths in the remote mode, which may partly explain efficiency gains without sacrificing process quality (Irvine et al., 2020).

Findings from workplace and occupational health syntheses also align with the dissertation's observation that mental health outcomes respond well to digital formats. An umbrella review of systematic reviews in workplace settings concluded that digital interventions show effectiveness for stress, anxiety, depression, burnout, and psychological well-being, while effectiveness is influenced by technology type, guidance, tailoring, and demographics (Cameron et al., 2025). However, the included reviews were predominantly low to critically low in methodological quality, and outcome heterogeneity limits strong inferences about clinical significance and productivity endpoints. A systematic review focused on occupational health care identified mental health as a particularly suitable target for digital interventions, with online training and software-based programs highlighted as promising, and emphasized the need for consensus on outcome measures to improve comparability and translation to practice (Jern-Matintupa et al., 2025).

The dissertation's subgroup findings are mirrored by trials of tailored workplace interventions. A review of randomized studies of tailored digital programs at work found benefits for presenteeism, sleep, stress, and somatic symptoms, weaker but null effects for depression and anxiety in general worker samples, and significant reductions in depression and anxiety among employees with higher baseline psychological distress. The authors argued that tailoring and blended

models can support return to work and symptom relief, with anonymity and scalability as additional facilitators of uptake and reach; they also documented high heterogeneity in productivity measurement and called for harmonization (Moe-Byrne et al., 2022). These observations resonate with the dissertation's moderation patterns by age and employment status and the emphasis on digital literacy as a likely mediator of effect.

For physical rehabilitation outcomes, the dissertation's evidence that digital aftercare can sustain or amplify early health gains without consistent superiority for physical indicators is compatible with the physiotherapy literature. A systematic review comparing telerehabilitation with face-to-face therapeutic exercise found no clinically relevant differences for functionality and quality of life, together with high patient satisfaction and adherence; studies varied in tools and pathologies, and few evaluated costs, which the authors identified as a gap for future work (Muñoz-Tomás et al., 2023). This parity at the level of functional outcomes supports the dissertation's interpretation that digital aftercare can be integrated into established orthopedic pathways without compromising core rehabilitative goals.

Two cross-cutting findings from the external literature reinforce the dissertation's methodological reflections. First, even when pooled effects favor digital delivery, several reviews note risks of performance and detection bias that are inherent to behavioral trials without blinding, as well as publication bias that cannot be ruled out. These patterns match the dissertation's caution about causal inference and the need for robust randomized designs and longer follow-up in the German context (Luo et al., 2020). Second, outcome heterogeneity and the limited reporting of absenteeism and presenteeism impede cumulation. Recent umbrella and occupational health reviews explicitly recommend standard sets such as workplace-relevant productivity measures to support benchmarking and policy decisions (Cameron et al., 2025).

Taken together, the convergence between dissertation findings and the contemporary literature supports a strategic shift toward hybrid, tailored, and digitally enabled models within the German rehabilitation system. It also underscores the need for rigorous, longer-term trials with standardized outcomes and cost-effectiveness analyses to inform scale-up decisions by the German Pension Insurance.

## Role of Digital Health Literacy

The findings of this dissertation underscore the central role of digital health literacy in shaping the effectiveness of digital interventions. Younger participants, who are typically more familiar with technology, profited disproportionately from digital prevention and aftercare programs, while older participants showed stronger improvements in conventional formats. This pattern suggests that the success of digital interventions is not only determined by program design but also by the technological readiness of the target population. Importantly, digital health literacy was not directly assessed in the studies included in this dissertation, which precludes empirical tests of its mediating role. Nevertheless, the consistent age-group differences observed across studies strongly suggest that digital competencies function as enabling conditions influencing uptake, adherence, and the translation of program content into sustained behavior change.

Recent international evidence further supports this interpretation. A systematic review and meta-analysis by K. Kim et al. (2023) demonstrated a moderate positive correlation between eHealth literacy and health-related behaviors ($r = 0.31$), with particularly strong associations for health-promoting behaviors such as physical activity and stress management. Older adults with higher digital literacy showed better engagement in health-promoting behaviors, contradicting the assumption that age alone is a barrier; instead, the decisive factor appears to be competence in navigating digital health information (K. Kim et al., 2023). This aligns with the present dissertation's finding that age-related differences in outcomes are likely proxies for underlying digital literacy gaps.

The umbrella review by König et al. (2025) emphasizes that digital health inequalities persist across socio-demographic groups, with age, gender, income, and education acting as important moderators of digital intervention effectiveness. Their synthesis showed that men often benefitted more than women, and that socioeconomic disadvantage and rural residence amplified barriers to digital health use. This suggests that digital literacy cannot be considered in isolation but must be embedded in the broader context of the "digital divide," encompassing access, skills, and benefits. Without targeted strategies to address these inequalities, digital interventions risk reproducing or even widening existing health disparities (König et al., 2025).

From the perspective of patient experience, Madanian et al. (2023) highlight that patients view empowerment, self-management, and personalization as key facilitators of digital health tool uptake. Conversely, limited digital and health literacy and concerns about privacy and usability are major barriers to sustained engagement. These findings mirror the barriers inferred in this dissertation: while digital programs offer flexibility and autonomy, participants without

adequate digital literacy may struggle to engage meaningfully or may disengage prematurely. Importantly, Madanian et al. (2023) recommend participatory design approaches that involve patients directly in development to ensure usability and relevance, an approach that could help bridge literacy gaps in rehabilitation aftercare.

Finally, Boucher and Raiker (2024) provide a nuanced view of engagement and retention in digital mental health interventions, showing that engagement is highly variable and shaped by user characteristics, perceived needs, and program design. They caution against simplistic assumptions that higher engagement always translates into better outcomes, but emphasize the importance of fostering optimal patterns of use. Their review also identifies a subgroup of "superusers" who maintain high engagement, suggesting that individuals with higher digital competence may both engage more and derive greater benefit. This resonates with the current dissertation's findings that younger, digitally literate participants derived greater benefits from digital programs, while older participants were more prone to attrition or reliance on conventional services (Boucher & Raiker, 2024).

Taken together, these findings suggest that digital health literacy is a critical mediator in the success of digital prevention and rehabilitation aftercare programs. It influences not only whether participants can access and navigate interventions but also whether they sustain meaningful engagement over time. The evidence points to several priorities: (1) systematically measuring digital health literacy in future rehabilitation studies; (2) tailoring interventions to participants' digital competencies; and (3) offering preparatory training modules to enhance digital health literacy prior to program initiation. Such steps would not only increase equity in access but also maximize the effectiveness and sustainability of digital health interventions within institutional frameworks like the German Pension Insurance.

## Complementarity of Digital and Conventional Programs

The results of this dissertation demonstrate that conventional programs remain relevant and necessary, particularly for older populations and individuals who benefit from interpersonal contact and structured group-based support. At the same time, digital formats have proven to be at least as effective as conventional ones, and in some domains superior, especially in promoting work ability and mental health in younger and more digitally literate participants. This indicates that digital and conventional interventions should not be viewed as competing but as complementary approaches, where hybrid models that combine digital flexibility with social support from face-to-face formats represent the most promising pathway for future rehabilitation and prevention practice.

The international evidence strongly reinforces this interpretation. (Berhe et al., 2025) conducted a meta-analysis of digital versus nondigital behavioral interventions for cardiovascular risk reduction and found that, on average, both approaches were equally effective in reducing risk factors. However, digital interventions showed advantages in specific domains such as body weight, blood glucose, and cholesterol reduction. These findings align with the results of this dissertation: digital formats can yield sharper improvements in certain health outcomes, yet the overall parity with conventional approaches underscores their complementary rather than substitutive role (Berhe et al., 2025).

Similarly, Jaswal et al. (2024) synthesized evidence on telerehabilitation compared to in-person rehabilitation and reported no significant differences in outcomes for physical functioning, mental health, and pain reduction. This corresponds closely to the findings of the present dissertation, where both digital and conventional programs improved health and work ability, with no universal superiority of either approach. Importantly, Jaswal et al. (2024) also noted that telerehabilitation was sometimes perceived as less effective for occupational and physical therapy, highlighting that the added value of digital formats depends on context and target population.

Building on this parity, blended or hybrid models appear particularly promising. Yang et al. (2023) provided a systematic review and meta-analysis showing that blended interventions combining face-to-face and eHealth components significantly improved physical activity, diet quality, and weight-related outcomes compared to controls. Their findings support the view that hybrid approaches can leverage the strengths of both formats: digital modules extend accessibility and promote self-management, while in-person sessions maintain motivation, accountability, and individualized support (Yang et al., 2023).

The study by Duan et al. (2025) further strengthens this perspective in the context of older adults. Their randomized controlled trial in Hong Kong demonstrated that a blended intervention outperformed both stand-alone digital and face-to-face interventions in promoting diet and physical activity. Importantly, older participants showed high adherence and acceptability in the blended format, despite known barriers to stand-alone eHealth programs. This directly resonates with the dissertation's findings that older participants benefited more from conventional formats, but could still engage

successfully in digital interventions when these were embedded in hybrid models that mitigated literacy barriers (Duan et al., 2025).

Taken together, the evidence from this dissertation and international studies underscores the necessity of moving beyond the dichotomy of digital versus conventional rehabilitation and prevention. Instead, complementarity should be the guiding principle: digital programs expand reach, flexibility, and efficiency, while conventional formats secure interpersonal interaction, structure, and accessibility for populations with lower digital readiness. Hybrid interventions offer the opportunity to balance these elements and deliver more equitable and sustainable outcomes.

## Sustainability of Intervention Effects

Sustainability of effects represents a major challenge across both digital and conventional programs. The results of this dissertation indicate that improvements in mental health, physical health, and work ability tended to decline or plateau after the end of structured interventions. This trajectory illustrates the well-documented "decay of treatment effects" in rehabilitation research and emphasizes the importance of strategies such as long-term adherence support, booster sessions, and the promotion of autonomous health behaviors (Hennessey & Rumrill, 2003). Sustaining gains beyond the intervention phase thus remains an open research and practice priority.

At the same time, it must be acknowledged that the study presented in Papers II and III employed a relatively short time interval for assessing sustainability, with follow-up periods limited to four months rather than years. While these time frames permitted conclusions about short- and medium-term developments, they are insufficient to capture the full trajectory of maintenance or relapse. To estimate sustainability more reliably, future research should adopt longer follow-up periods with multiple measurement points, ideally extending over several years. Such designs would enable a more detailed understanding of how intervention effects evolve, the timing and magnitude of potential declines, and the factors that predict long-term maintenance of health and work ability gains.

The broader evidence base provides additional insights into this challenge. Mönninghoff et al. (2021) reviewed mHealth physical activity interventions and showed that while small-to-moderate effects on physical activity were sustained in the long term, effect sizes declined over time. This parallels the dissertation's findings of early improvements in health and work ability that diminished after structured support ended. Similarly, Mamukashvili-Delau et al. (2023) found that internet-based CBT for depression produced not only short-term benefits but also maintained small yet significant long-term improvements in depressive symptoms and quality of life, suggesting that digital formats can sustain gains when interventions are designed with long-term adherence in mind.

Seward et al. (2025) provide further nuance by identifying mechanisms that influence sustainability in digital mental health interventions. Their causal mediation analysis was based on the CONEMO trials, two large randomized studies conducted in Brazil and Peru that evaluated a low-intensity digital mental health intervention for patients with depression comorbid with diabetes or hypertension. The trials initially showed significant improvements in depressive symptoms at three months, but these effects diminished by six months. Seward et al. demonstrated that understanding session content without difficulty and completing enjoyable, self-selected activities mediated long-term improvements in depression outcomes. These findings highlight that sustained effectiveness depends not only on the formal duration of an intervention but also on user comprehension, digital literacy, and engagement with meaningful activities. They resonate with this dissertation's conclusion that booster sessions and strategies to promote autonomous health behaviors are essential to maintain gains after the end of structured programs. Moreover, the CONEMO evidence suggests that optimizing usability and tailoring content to diverse literacy levels are critical levers to enhance the sustainability of digital rehabilitation interventions.

The social dimension also plays a role for sustainability of effects. Hansen et al. (2025) showed that digital interventions for loneliness were effective when they incorporated group or social components, but their long-term sustainability remained uncertain due to limited follow-up data. This suggests that interventions that combine social connectedness with digital flexibility may be better equipped to maintain benefits over time, which aligns with the dissertation's emphasis on hybrid models. Finally, the umbrella review by Fiedler et al. (2020) stressed that e/mHealth interventions in prevention are most effective when grounded in theoretical frameworks, tailored to users, and supported by social contexts. Although their review highlighted a lack of long-term evaluations, the identification of theoretical foundations and social embedding as critical determinants of sustainability strengthens the argument that simply providing digital access is insufficient; interventions must be systematically designed to encourage durable behavior change.

Taken together, both the dissertation and the international evidence point to a shared conclusion: sustainability is the Achilles' heel of digital and conventional interventions alike. While initial improvements are achievable, without ongoing reinforcement, effect sizes decline, and behaviors relapse. Sustained gains require (1) long-term follow-up studies that track trajectories over years rather than months, (2) booster sessions and adaptive support mechanisms to reinforce learned behaviors, (3) embedding social and group-based components to prevent disengagement, and (4) tailoring interventions to digital literacy levels and user comprehension to ensure participants can engage autonomously. For the German rehabilitation system and the DRV, this implies that digital and hybrid aftercare programs should be designed not only for short-term effectiveness but also with embedded mechanisms that facilitate long-term sustainability.

# Broader Practical and Policy Implications

The findings of this dissertation have implications that extend beyond the academic discourse and directly inform the practice and policy of rehabilitation in Germany. The results highlight both opportunities and challenges in the use of digital and conventional programs in prevention and aftercare. They speak to the future direction of the German Pension Insurance, employers and workplaces, and rehabilitation clinics and providers.

## Implications for the DRV and German Rehabilitation Policy

The results consistently show that digital formats are at least as effective as conventional programs in improving mental health, physical health, and work ability, and in some cases even superior (Berhe et al., 2025; Jaswal et al., 2024). This evidence supports the strategic modernization of rehabilitation services under the DRV, which faces increasing demographic and structural challenges. At the same time, the findings also reveal significant heterogeneity across subgroups: younger participants and those with higher digital literacy benefitted more from digital interventions, whereas older individuals and those less familiar with technology profited more strongly from conventional programs. These patterns suggest that rehabilitation policy must move away from "one-size-fits-all" solutions and toward differentiated and hybrid program structures.

In practical terms, the DRV should allocate resources according to subgroup characteristics such as age, gender, and employment status. Younger and unemployed participants may profit most from digital programs, while conventional formats remain indispensable for older patients or those requiring interpersonal contact. To ensure equitable access, strengthening digital literacy and infrastructure must be a priority. Without targeted support for patients with lower levels of digital competence, the expansion of digital services risks reproducing existing inequalities in healthcare access and outcomes.

These findings resonate with ongoing policy developments within the DRV, particularly the framework of DigiFlexReha (DRV, 2024). Conceived as a flexible rehabilitation model that integrates digital components into medical rehabilitation, DigiFlexReha aims to combine the strengths of digital accessibility with the quality standards of conventional rehabilitation. The empirical evidence presented here lends weight to such initiatives by demonstrating that digital formats are effective, but it also highlights critical areas, such as sustainability of effects and subgroup differences, that must be addressed for DigiFlexReha and similar models to succeed in practice. In this sense, the dissertation offers both scientific validation and important cautions for the policy agenda currently unfolding in German rehabilitation.

## Implications for employers and workplaces

Workplaces represent an important arena for prevention. The results of Study I demonstrated that both digital and conventional prevention programs can improve work ability and mental health among employees with initial impairments. For employers, this underscores the value of investing in preventive health programs, not only to reduce absenteeism but also to sustain long-term employability.

However, the differential effects across age groups have direct implications for the design of workplace health programs. Younger employees are likely to benefit more from digital elements that offer flexibility and autonomy, while older employees may require conventional, face-to-face contact formats to achieve similar benefits (Madanian et al., 2023). Employers should therefore adopt a dual strategy: integrating scalable digital elements while retaining

interpersonal modules that address the needs of older and less digitally literate employees. Hybrid prevention models within occupational health management could optimize effectiveness across a diverse workforce (Bradley et al., 2016).

## Implications for Clinics and Providers

For rehabilitation clinics and service providers, the findings underline the necessity of developing hybrid care pathways (Keteyian et al., 2022). Digital aftercare formats such as digIRENA showed particular strengths in enhancing participation and adherence, but they also faced challenges in sustaining effects once structured support ended. Clinics should therefore combine digital modules with conventional treatment, allowing patients to move flexibly between formats depending on their progress, preferences, and life circumstances (Yang et al., 2024).

In addition, providers need to invest in training their staff to deliver high-quality digital interventions (Kulju et al., 2024). This requires not only technical competencies but also the ability to maintain therapeutic relationships in digital environments (Torous & Hsin, 2018). Clinics must establish robust monitoring systems to track adherence and health outcomes in both digital and conventional programs. Effective feedback loops, crisis management protocols, and options for switching back to in-person treatment are crucial to maintaining quality and safety. These measures are consistent with the quality requirements outlined in current DRV policy frameworks for medical rehabilitation (DRV, 2009), and their implementation will determine whether digital rehabilitation can be sustainably integrated into routine practice.

## Outlook

Taken together, the findings suggest that the future of prevention and rehabilitation lies in adaptive, hybrid, and patient-centered models (DRV, 2024). Digital programs can expand accessibility and flexibility, while conventional formats remain essential for patients who benefit from structured interpersonal care. However, sustainability of intervention effects remains the central challenge: both digital and conventional aftercare showed declining benefits after program completion. Addressing this challenge will require innovative strategies, such as booster sessions, stepped-care approaches, and long-term digital monitoring, to extend treatment gains beyond the formal intervention period.

In this context, policy initiatives such as DigiFlexReha represent an important step toward institutionalizing flexible, hybrid models within the German rehabilitation system. Yet, the success of these models will depend on how well they integrate empirical insights on subgroup differences, digital literacy, and sustainability into their design and implementation (Fiedler et al., 2020; Seward et al., 2025). By combining digital flexibility with conventional strengths, future rehabilitation services can meet the diverse needs of patients while maintaining the high quality and equity standards of the German healthcare system.

# Methodological Reflections

The three empirical studies included in this dissertation were conducted in applied rehabilitation and prevention settings and therefore combine methodological strengths with limitations inherent to practice-oriented research. Reflecting on these aspects is essential for interpreting the findings and for guiding future research.

A first strength lies in the large sample sizes and the longitudinal designs employed in all studies. With participant numbers exceeding one thousand in the rehabilitation aftercare studies and several hundred in the prevention study, the analyses achieved adequate statistical power to detect small to moderate effects and to examine subgroup differences (Jekauc et al., 2021). The longitudinal perspective, spanning several measurement points over up to 12 months, allowed for the assessment of temporal trends and the detection of both immediate and medium-term intervention effects.

Second, the studies were conducted in real-world rehabilitation and prevention contexts under the auspices of the German Pension Insurance. This enhances the external validity of the findings and ensures their direct relevance to policy and practice. The inclusion of multiple outcomes, work ability, physical health, and mental health, provides a multidimensional view on intervention effectiveness (Mewes et al., 2012) and reflects the holistic goals of medical rehabilitation (Wade, 2015).

Nevertheless, several limitations must be acknowledged. The most important concerns the quasi-experimental study designs. Although efforts were made to include comparison groups, randomization was only partially achieved, leading

to potential self-selection bias. Particularly in the aftercare studies, allocation to conventional aftercare (IRENA) was non-random, reflecting real-world patient choices and clinic availability. While this increases ecological validity, it limits internal validity and causal inference.

A further limitation is attrition, which is common in longitudinal rehabilitation research but nevertheless constrains the generalizability of results. Although dropout analyses suggested largely random patterns of missingness, selective attrition cannot be fully excluded. In addition, blinding of participants and providers was not possible given the nature of the interventions, which may have introduced expectancy effects.

Measurement also represents a limitation. All primary outcomes, work ability, physical health, and mental health, were assessed through self-report instruments. While these instruments are validated and widely used, they are subject to biases such as social desirability and recall error (Fisher, 1993). Moreover, reliance on self-reports precludes the detection of objective physiological changes or workplace reintegration outcomes. Finally, the follow-up periods were limited to short- and medium-term intervals. Sustained effects beyond one year could not be assessed, which leaves open the question of long-term intervention sustainability.

These limitations suggest several directions for future research. First, randomized controlled trials are needed to strengthen causal inference and reduce biases related to self-selection. Second, cost-effectiveness analyses should complement effectiveness studies to provide economic evidence for policy decisions, particularly given the resource constraints of rehabilitation systems. Third, future studies should include objective health measures, such as clinical biomarkers, physical performance tests, or employer-verified return-to-work data, to triangulate self-report findings and enhance validity. Finally, longer-term tracking of participants is essential to assess the durability of intervention effects and to identify factors that support or hinder sustainability.

# Future Research Directions

The present dissertation has shown that digital prevention and aftercare programs can be as effective as, and in some domains superior to, conventional programs. At the same time, it has revealed important limitations and raised new questions that future research must address. The following areas are of particular importance for the advancement of rehabilitation science and practice.

## Long-Term Sustainability of Digital Aftercare

A major finding across the aftercare studies was that improvements in physical and mental health and work ability tended to decline after the end of the intervention phase. This “decay of treatment effects” is a well-documented phenomenon in rehabilitation (Paolucci et al., 2001), but its mechanisms remain insufficiently understood in digital formats. Future research should investigate whether the inclusion of booster sessions, step-down programs, or ongoing low-intensity digital support can extend the effects of digital aftercare beyond twelve months. Long-term follow-ups, ideally extending to two or three years, would allow for a more precise understanding of sustainability and relapse dynamics. Such research should also consider how digital intervention interacts with workplace conditions, social support, and individual motivation over time.

In addition, digital healthcare services offer the possibility of being provided on a low-threshold basis over extended periods. Unlike conventional programs, which are typically bound to fixed schedules and institutional settings, digital technologies can deliver continuous or intermittent support in flexible, user-centered ways (Marciniak et al., 2024). Examples include mobile applications with push notifications (Freyne et al., 2017), chatbots providing motivational prompts (Aggarwal et al., 2023), online exercise libraries (Cugelman et al., 2011), or teleconsultations available on demand (Arevian et al., 2018). Such services could be implemented with relatively low resource requirements once the infrastructure is established, making them scalable and cost-efficient. Importantly, the low-threshold nature of digital offerings reduces barriers related to geography, time constraints, or stigma, and allows patients to re-engage with supportive content whenever they experience difficulties in maintaining healthy routines. In this way, digital technologies open up new opportunities to foster long-term adherence and to counteract the decline of intervention effects after structured programs have ended (Blakey et al., 2018).

## Mechanisms of Adherence and Engagement

Adherence is one of the most decisive factors for the success of digital rehabilitation programs. Although digital platforms such as digIRENA provide greater flexibility and accessibility, not all patients sustain regular engagement over time. Previous research has highlighted the importance of motivational elements such as goal-setting, personalized feedback, gamification, social support networks, and therapist-patient communication via digital channels in fostering adherence. Furthermore, the use of intensive longitudinal methods can capture real-time fluctuations in motivation and adherence (Bolger & Laurenceau, 2013), providing a more dynamic understanding of engagement patterns (Jekauc et al., 2025). Beyond these applied features, however, theoretical frameworks are necessary to explain why patients either persist or disengage from prevention and aftercare programs.

Dual-process theories of health behavior provide a useful lens for conceptualizing adherence. The Affective-Reflective Theory developed by Brand and Ekkekakis (2018) emphasizes that momentary affective responses, such as the immediate pleasure or displeasure associated with exercise, influence subsequent decisions about whether to continue or disengage. Situated decisions regarding participation are thus not solely the product of rational deliberation but are strongly shaped by affective impulses. This perspective aligns with the observation that patients who experience positive affect during digital aftercare sessions are more likely to re-engage, whereas those who encounter negative experiences often drop out. Similarly, the Physical Activity Adoption and Maintenance model proposed by Strobach et al. (2020) advances the idea that adherence and maintenance are the result of both explicit processes (e.g., intentions, self-regulation, executive functions) and implicit processes (e.g., affective reactions, habit formation). In the context of digital rehabilitation, adherence is therefore best understood as a dynamic interplay between explicit intentions and automatic implicit impulses.

Recent conceptual advancements further refine this perspective. Jekauc et al. (2025) introduced a multidimensional framework for analyzing the intention–behavior gap, emphasizing the dynamic variability of intentions and their enactment across different contexts and time points. This model underscores that intention is not a static construct but fluctuates within individuals across daily or weekly episodes. Applying this framework to prevention and rehabilitation aftercare suggests that adherence should be examined not only at the aggregate level (e.g., overall completion rates) but also as a sequence of behavioral episodes (e.g., attending weekly sessions). Intensive longitudinal data, with high-frequency measurements of intentions and behaviors, are therefore necessary to capture the within-person processes that explain why adherence is sustained at some points but falters at others.

Implicit processes, particularly habit formation, also play a crucial role in adherence. As shown by Weyland et al. (2022), positive affective responses are linked to the development of exercise instigation habits, which in turn predict more stable behavioral engagement. Digital tools can support this process by facilitating repeated positive experiences – for example, through self-selected activities, competence-enhancing feedback, or interactive and socially rewarding program features. By systematically fostering positive affect, digital interventions may accelerate the transition from deliberate intention-driven behavior to more automatic, habitual engagement (Strobach et al., 2020). This is particularly important for sustaining adherence once the novelty of the program wears off and motivational fluctuations emerge.

Taken together, adherence in digital prevention and aftercare programs should be understood as the outcome of intertwined reflective and automatic processes. Intentions guide initial participation, but implicit mechanisms, such as affective responses and habit formation, determine long-term engagement. Digital interventions are well positioned to address both levels simultaneously: they can strengthen explicit processes through goal-setting, reminders, and feedback while also cultivating implicit pathways by ensuring enjoyable and rewarding experiences. Future research should employ intensive longitudinal designs to disentangle these processes, test dual-process theoretical predictions, and identify program features that most effectively promote sustained adherence across diverse patient groups.

## Subgroup-Specific Designs and Tailoring

The results of the empirical studies showed that subgroup characteristics such as age, gender, and employment status moderate the effectiveness of interventions. Younger and unemployed individuals benefited more from digital programs, while older individuals profited more from conventional formats. This points to the need for subgroup-specific designs. Future research should test adaptive intervention models, where allocation to digital, conventional, or hybrid formats is based on demographic, clinical, and psychosocial profiles (Fouyaxis et al., 2024). Tailoring could also occur within digital programs, for instance by adapting the pace, intensity, and communication style to user

characteristics (Cheung et al., 2019). Such designs would increase precision and efficiency in rehabilitation, moving toward a personalized medicine approach.

Subgroup-specific tailoring should therefore not only match interventions to demographic or psychosocial characteristics but also address the distinct regulatory needs across phases of behavior change (Michie et al., 2017). For example, younger and digitally literate individuals may require initial support in structuring intentions and self-regulation strategies in digital environments, while older participants or those with weaker self-regulatory abilities may need additional interpersonal guidance to ensure translation of intentions into behavior. Once adoption is achieved, digital tools can further promote maintenance by strengthening implicit processes, for instance through affect-enhancing features or habit-supportive repetition. Thus, tailoring must be dynamic and phased, acknowledging that different mechanisms drive adherence and maintenance across subgroups (Strobach et al., 2020).

## Digital Health Literacy as a Key Determinant

The studies in this dissertation revealed age-related differences in the effectiveness of digital programs, with younger participants profiting more strongly. This suggests that digital health literacy is a critical determinant of outcomes. Digital health literacy encompasses not only technical skills but also the ability to evaluate digital health information, integrate it into daily routines, and use digital platforms for self-management (van der Vaart & Drossaert, 2017). At present, however, there is no validated instrument available for measuring digital health literacy specifically in the context of rehabilitation and prevention, which represents a significant methodological gap. Future research should therefore prioritize the development of such instruments and examine interventions aimed at increasing digital health literacy, particularly among older or socioeconomically disadvantaged groups. Addressing this factor is essential to prevent digital health innovations from reinforcing social inequalities in access and effectiveness.

In addition, digital health literacy can be understood as a dynamic capability that interacts with the processes of adoption and maintenance of health behaviors (J. Kim et al., 2023). While younger participants may rely more naturally on digital tools due to higher familiarity, older or less digitally literate groups could benefit from preparatory interventions that strengthen competencies before engaging in digital prevention or aftercare. Such preparatory modules might include basic training in the use of digital devices, guided practice in navigating health platforms, or exercises in critically evaluating health information online (Boshnjaku et al., 2025). Embedding digital literacy support into rehabilitation pathways would not only reduce entry barriers but also enhance adherence and long-term engagement, particularly in hybrid models that integrate digital and face-to-face components. Thus, fostering digital health literacy should be viewed as an integral part of rehabilitation strategies, complementing medical and psychosocial interventions to maximize equity and effectiveness.

## Integration of Hybrid and AI-Personalized Models

The future of rehabilitation is likely to lie in hybrid models that strategically combine digital and face-to-face components. Such approaches allow programs to leverage the flexibility, scalability, and accessibility of digital interventions while retaining the interpersonal support and structure of conventional care (Yang et al., 2024). Hybrid models can be tailored to patient needs by, for example, initiating rehabilitation with face-to-face sessions to establish routines, trust, and interpersonal accountability, followed by digital modules to support long-term maintenance (Duan et al., 2025). The DigiFlexReha initiative represents a current effort in this direction within the German rehabilitation system, aiming to flexibilize program delivery through the integration of digital phases alongside conventional elements (DRV, 2024). Future research should examine which sequences and intensities of hybrid models are most effective for different patient subgroups, and how they can best support long-term sustainability of health and work ability outcomes.

At the same time, advances in artificial intelligence (AI) open new opportunities for highly personalized rehabilitation (Alshami et al., 2025). AI systems could continuously analyze patients' daily data on physical state (e.g., activity levels, fatigue, biometrics), psychological well-being (e.g., mood, stress), and motivational fluctuations to dynamically adapt program content and delivery. For instance, AI could adjust exercise intensity on days of reduced physical capacity, provide motivational prompts when adherence wanes, or suggest relaxation techniques when psychological strain is detected. Such individualized adjustments could increase both effectiveness and adherence by aligning rehabilitation with real-time patient needs. However, rigorous evaluation is required to assess not only clinical efficacy but also the

ethical, privacy, and acceptability implications of AI-driven personalization, ensuring that technological innovations remain aligned with patient autonomy and trust (Attoh-Mensah et al., 2025).

### Comparative Cost-Effectiveness Studies

Finally, the widespread implementation of digital rehabilitation programs requires robust evidence on their cost-effectiveness. While clinical outcomes are central, policymakers and insurers such as the DRV must also consider economic implications. Future studies should integrate health economic evaluations that compare digital, conventional, and hybrid interventions in terms of direct costs (e.g., staff, infrastructure, digital platforms) and indirect benefits (e.g., reduced sick leave, extended work participation, delayed retirement) (Gega et al., 2022). Cost-effectiveness studies should also examine whether digital formats provide particular advantages in rural areas, where access to conventional rehabilitation is limited (Maita et al., 2024). Such analyses will be crucial to inform reimbursement models and long-term policy planning.

## Conclusion

The overarching contribution of this dissertation lies in demonstrating that digital prevention and aftercare programs are effective alternatives to conventional rehabilitation services and, in some cases, achieve superior outcomes. However, their effectiveness is not universal; rather, it depends on patient characteristics such as age, gender, and employment status, as well as on sustained engagement beyond the structured intervention phase. Digital interventions thus hold substantial promise but require careful tailoring and long-term support strategies to fully realize their potential.

From a scientific perspective, the dissertation provides robust longitudinal evidence from the German rehabilitation system, addressing a gap in the international literature on digital health interventions. By integrating findings from large-scale quasi-experimental studies within the institutional framework of the Deutsche Rentenversicherung, it enriches the global debate on digital health and rehabilitation. It advances theoretical understanding of how digital formats interact with demographic and contextual factors to influence work ability, physical health, and mental health.

For practice and policy, the results offer direct guidance for the DRV and related institutions. They support the integration of digital programs into routine care, while at the same time highlighting the continued relevance of conventional programs for certain subgroups. The findings underscore the necessity of differentiated and hybrid approaches, as well as the importance of fostering digital health literacy to ensure equitable access. They therefore provide a sound evidence base for the DRV in the evidence-based design of prevention and rehabilitation strategies, including current innovation frameworks such as DigiFlexReha.

Looking ahead, the central challenge for prevention and rehabilitation lies in developing hybrid, tailored, and sustainable models. Such models must combine the scalability and flexibility of digital programs with the interpersonal strengths of conventional care, while ensuring long-term adherence and effectiveness. By addressing demographic change, growing health system demands, and increasing expectations for patient-centered care, these models represent a promising path toward safeguarding employability and health in the coming decades.

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