JYU DISSERTATIONS 634

Maarit Janhunen

Exergame-Based Rehabilitation in Older Adults Specifically after Total Knee Replacement

UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF SPORT AND
HEALTH SCIENCES

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Esitetään Jyväskylän yliopiston liikuntatieteellisen tiedekunnan suostumuksella
julkisesti tarkastettavaksi Liikunta-rakennuksen auditoriossa L304
toukokuun 5. päivänä 2023 kello 12.

Academic dissertation to be publicly discussed, by permission of
the Faculty of Sport and Health Sciences of the University of Jyväskylä,
in building Liikunta, auditorium L304, on May 5, 2023, at 12 o'clock.

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2023

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ISBN 978-951-39-9547-8 (PDF)
URN:ISBN:978-951-39-9547-8
ISSN 2489-9003

Permanent link to this publication: http://urn.fi/URN:ISBN:978-951-39-9547-8

To Milla and Mikko,

with love

ABSTRACT

Janhunen, Maarit
Exergame-Based Rehabilitation in Older Adults Specifically After Total Knee Replacement
Jyväskylä: University of Jyväskylä, 2023, 100 p. + original articles
(JYU Dissertations
ISSN 2489-9003; 634)
ISBN 978-951-39-9547-8 (PDF)

This thesis aimed to study the feasibility and effects of exergame-based rehabilitation on enhancing the physical function and pain in older adults, specifically after total knee replacement (TKR). The feasibility of exergames customized for the post-TKR rehabilitation was studied as movement characteristics, perceived exertion, and knee pain during exergaming in individuals who have undergone TKR (n=7, mean age, 65 years). The effects of exergame-based rehabilitation on walking were assessed in a systematic review and meta-analysis in older adults without neurologic conditions (n=3797, mean age, 74 years), and on mobility and other physical function in a home-based 4-month randomized controlled trial (RCT) in individuals undergoing TKR (n=52, mean age, 66 years). In the meta-analysis, the groups that underwent exergame-based rehabilitation were compared with reference groups that performed other types of exercise or did not undergo any exercise. In the RCT, exergame-based rehabilitation was compared with standard post-TKR home exercise.

The results of the feasibility study showed that although the volume and intensity of movement was mostly higher during exergaming, the range of movement was similarly achieved during exergaming and standard exercising, all with low levels of perceived exertion and pain. The meta-analysis showed that the exergame-based interventions implemented in a supervised or unsupervised manner were more effective on improvements in walking than other types of exercise or no exercise. The results of the RCT study showed that the unsupervised, exergame-based intervention was more effective on improvements in mobility and as effective as standard home exercise on enhancing other physical functions and pain.

In conclusion, in older adults, exergaming resulted in positive effects on physical function, especially on walking and mobility, in both supervised and unsupervised rehabilitation using customized or commercially available exercise games. Moreover, the exergames may be customized to achieve the movement characteristics appropriate for post-TKR rehabilitation. Exergames may be considered as a promising form of exercise in the management of the physical function and pain in the older adults as an alternative to standard exercise, specifically for rehabilitation after TKR.

Keywords: physical therapy, video games, kinematics, physical function, pain

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Janhunen, Maarit
Liikuntapelit ikääntyvien aikuisten kuntoutuksessa erityisesti polven tekonivelleikkauksen jälkeen
Jyväskylä: Jyväskylän yliopisto, 2023, 100 s. + alkuperäiset artikkelit
(JYU Dissertations
ISSN 2489-9003; 634)
ISBN 978-951-39-9547-8 (PDF)

Tämän väitöskirjatutkimuksen tavoitteena oli tutkia liikuntapelien käytettävyyttä ja vaikuttavuutta ikääntyneiden aikuisten fyysisen toimintakyvyn ja kivun paranemiseen erityisesti polven tekonivelleikkauksen jälkeen. Käytettävyyttä tutkittiin liikeominaisuuksina, havaittuna rasituksena ja polvikipuna peliharjoittelun ja tavanomaisen harjoittelun aikana henkilöillä, joille oli tehty polven tekonivelleikkaus (n=7, keski-ikä 65 vuotta). Peliharjoittelun vaikuttavuutta kävelyyn tutkittiin systemaattisella kirjallisuuskatsauksella ja meta-analyysilla henkilöillä, joilla ei ollut neurologisia sairauksia (n=3797, keski-ikä 74 vuotta), sekä liikkumis- ja toimintakykyyn neljä kuukautta kestäneellä satunnaistetulla kontrolloidulla interventiotutkimuksella (RCT) henkilöillä, joille tehtiin polven tekonivelleikkaus (n=52, keski-ikä 66 vuotta). Meta-analyysissa peliharjoittelua tekeviä ryhmiä verrattiin ryhmiin, joilla oli muun tyyppistä harjoittelua tai jotka eivät harjoitelleet. RCT-tutkimuksessa peliharjoittelua tekevää ryhmää verrattiin ryhmään, joka teki tavanomaista, leikkauksen jälkeistä kotiharjoittelua.

Käytettävyystutkimuksen tulokset osoittivat, että vaikka liikkeen määrä ja intensiteetti olivat enimmäkseen korkeammat peliharjoittelun aikana, liikkeen laajuus oli samanlainen peliharjoittelun ja tavanomaisten harjoitusten aikana. Harjoittelun aikainen rasitus ja kipu olivat vähäistä. Meta-analyysi osoitti, että ohjattu tai itsenäisesti suoritettu peliharjoittelu paransi kävelyä tehokkaammin kuin muun tyyppinen harjoittelu tai se, että ei harjoiteltu. RCT-tutkimuksessa havaittiin, että peliharjoittelu paransi liikkumiskykyä ja oli yhtä tehokasta kuin tavanomainen harjoittelu muun fyysisen toimintakyvyn ja kivun paranemisessa.

Yhteenvetona voidaan todeta, että fyysinen toimintakyky, erityisesti kävely ja liikkumiskyky paranevat ikääntyneillä aikuisilla ja polven tekonivelleikkauksen jälkeisessä kuntouksessa, jossa käytetään liikuntapelejä ohjatusti tai itsenäisenä harjoitteluna. Lisäksi liikuntapelejä voidaan mukauttaa saavuttamaan polven tekonivelleikkauksen jälkeiseen kuntoutukseen sopivat liikeharjoitteluominaisuudet. Liikuntapelejä voidaan pitää lupaavana harjoittelumuotona ikääntyneiden henkilöiden toimintakyvyn parantamisessa ja kivun hallinnassa vaihtoehtona muulle harjoittelulle erityisesti polven tekonivelleikkauksen jälkeisessä kuntoutuksessa.

Avainsanat: fysioterapia, videopelit, kinematiikka, fyysinen toimintakyky, kipu

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ACKNOWLEDGEMENTS

In 2018 I read a job advertisement looking for a doctoral student for the Business Ecosystems in Effective Exergaming (BEE) project studying digital rehabilitation. I realized that this is it! My chance and dream to grow as a researcher at the faculty, in which I had finished my master studies a few years earlier. I first want to thank the job interviewers, my supervisors Professor Ari Heinonen and Senior Researcher Eeva Aartolahti, who saw enthusiasm and potential in me, and who shared their expertise with me and encouraged and guided me throughout these years. You have been an important support for me and kept me on the main road also in times when I have been about to go offroad.

I had privilege to have Professor Stefan Bachmann and Associate Professor Nina Skjæret Maroni as the reviewers and Professor Eling D. de Bruin as the opponent of this thesis. You all are experts and top researchers in the field of rehabilitation, and I thank you for your time, effort, and valuable comments. Likewise, I am grateful to all my co-authors for your contribution to the original articles presented in this thesis. In addition, I want to thank all the individuals in Jyväskylä and Turku for participating into this study. Without you all as well as the BEE-project group, professionals in game design in the GameLab in the Turku University of Applied Sciences, professionals in the Turku University Hospital and in the Central Finland Hospital Nova, and the funding agencies Business Finland, Finnish collaboration companies, University of Jyväskylä and the Päivikki and Sakari Sohlberg foundation, this thesis would have not been possible. Thank you.

I also want to thank my co-workers and fellow doctoral students Outi Ilves, Niina Katajapuu, Heidi Pesonen, and especially Lilli’s six: Marjo-Riitta Anttila, Sari Honkanen, Mirjami Kantola, Katariina Pirnes and Sara Suikkanen. It has been a pleasure to get to know and do work with during these years. Thank you all for your friendship, support and those refreshing lunch and coffee breaks and gatherings under "work and fun". In addition, I want to thank all the co-workers who have been in the Physical therapy team of the Faculty of Sport and Health Sciences during these years.

Moreover, I want to thank my friends, Kitta Virolainen, my childhood friend and godmother of my firstborn, and Leena Liimatainen, Laura Reinilä and Pirjo Viljanen, my water running and walking buddies. You all have listened endlessly when I have got excited to talk about my thesis. Thank you for letting me do that.

Finally, I want to thank my children Milla and Mikko and my mother Ritva. Mom, you have listened to me in good times and bad and supported me throughout my life. Milla and Mikko, you are the most important thing in my life. Believe in yourselves as much as I believe in you. Keep dreaming and go for what you want - dreams tend to come true. I love you.

Jyväskylä, May 2023
Maarit Janhunen

ORIGINAL PUBLICATIONS AND AUTHOR CONTRIBUTION

This thesis is based on the following three original publications; a cross-sectional feasibility study, a systematic review, and meta-analysis with meta-regression, and a 4-month dual-center randomized controlled trial. The publications of these studies are referred to in the text by their Roman numerals:

I Janhunen M, Löppönen A, Walker S, Punsár T, Katajapuu N, Cheng S, Paloneva J, Pamilo K, Luimula M, Korpelainen R, Jämsä T, Heinonen A & Aartolahti E. (2022). Movement characteristics during customized exergames after total knee replacement in older adults. *Frontiers in Sports and Active Living* 4(915210), 1–12. https://doi.org/10.3389/fspor.2022.915210

II Janhunen M, Karner V, Katajapuu N, Niiranen O, Immonen J, Karvanen J, Heinonen A & Aartolahti E. (2021). Effectiveness of exergame intervention on walking in older adults: A systematic review and meta-analysis of randomized controlled trials. *Physical Therapy 101* (9), 1–11. https://doi.org/10.1093/ptj/pzab152

III Janhunen M, Katajapuu N, Paloneva J, Pamilo K, Oksanen A, Keemu H, Karvonen M, Luimula M, Korpelainen R, Jämsä T, Kautiainen H, Mäkelä K, Heinonen A & Aartolahti E. (2023). Effects of a home-based, exergaming intervention on physical function and pain after total knee replacement in older adults: a randomized controlled trial. *BMJ Open Sport & Exercise Medicine 9* (e001416), 1–9. https://doi.org/10.1136/bmjsem-2022-001416

This thesis is part of the Business Ecosystems in Effective Exergaming (BEE) project (1/2017–12/2020), which investigated the usability, feasibility, and effectiveness of various game-based rehabilitation methods using remote technology, such as custom-made exergames developed and used in the Studies I and III. BEE-project was the consortium and collaboration of the University of Jyväskylä, the Turku University of Applied Sciences, the University of Oulu, the Turku University Hospital, and the Central Finland Hospital Nova (former Central Finland Central Hospital). Business Finland, Finnish business partners, and universities funded the BEE-project. It was already underway when the author joined. The research group of the project had completed the study design, ethical approvals, and research permits for Studies I and III, and the data collection for Study I had begun.

The author participated in the preparation of the 4-month dual-center randomized controlled trial (Study III) by testing and developing used rehabilitation games in cooperation with the GameLab of the Turku University of Applied Sciences and partner companies, and by preparing a data management plan and data protection impact assessment for the study. In addition, the author was responsible for the consistency of the measurement protocol in the research centers in Turku and Jyväskylä, and its thorough documentation and guidance.

The author had the main responsibility for data collection and data management in Study I. The author continued the ongoing data collection in Study II and coordinated and mainly carried out the data collection for Study III in Jyväskylä. The author analyzed and interpreted the data for all the studies in collaboration with statisticians. The author was the corresponding author of Study II and III, and shared corresponding authorship of Study I with PhD student A. Löppönen.

FIGURES

TABLES

ABBREVIATIONS

10-MWT	10-meter walking test
BEE	Business Ecosystems in Effective Exergaming
CI	Confidence interval
IQR	Interquartile range
ITT	Intention-to-treat
METh	Metabolic equivalent of task hours
OA	Osteoarthritis
OKS	Oxford Knee Score
PA	Physical activity
RCT	Randomized controlled trial
ROM	Range of motion
RPE	Rating of perceived exertion
SD	Standard deviation
SMD	Standard mean difference
SPPB	Short Physical Performance Battery
TKR	Total knee replacement
TUG	Timed Up and Go
VAS	Visual analog scale
WOMAC	Western Ontario and McMaster Universities Osteoarthritis Index

CONTENTS

1 INTRODUCTION

The usage of exercise games, exergames, in the rehabilitation process has been shown to have several benefits, and there has been a growing interest in the use of exergames as a therapeutic exercise promoting the physical function of older adults (Cano Porras et al., 2018; Hai et al., 2022; Suleiman - Martos et al., 2022). For example, either commercially available exergames may be used (Reis et al., 2019) or exergames may be tailored for a specific group of patients (Pirovano et al., 2016), both providing visual and audio feedback on performance (Rutkowski et al., 2019; Yeşilyaprak et al., 2016). In addition, the progression of a rehabilitation process may be taken into account in exergames (Skjæret et al., 2016), and a rehabilitation process may be implemented at rehabilitees' homes (Perrochon et al., 2019). Moreover, rehabilitees have shown adherence on exergaming, which may contribute to its effect on the set rehabilitation goals (Pacheco et al., 2020).

However, the research of therapeutic exercise utilizing exergames has focused more on its effectiveness on rehabilitative outcomes than on the kinematics of the performance, i.e., on investigation the feasibility of the movements performed during gaming from the perspective of a specific rehabilitation need. It is already widely known about the effectiveness of exergame-based exercising on balance particularly in healthy older adults or in older adults with neurologic disorders (Cano Porras et al., 2018; Ong et al., 2021; Perrochon et al., 2019; Reis et al., 2019). There is a need to determine the possibilities of exergame-based training on enhancing other physical outcomes, such as walking, in older adults who do not have neurologic disorders. Furthermore, an investigation on whether exergames can be tailored for a certain group of rehabilitees, such as patients undergoing total knee replacement (TKR) surgery is essential.

The trend in the number of TKR surgeries has been growing in the recent decades and is predicted to increase further in the coming decades, especially among older adults (Ackerman et al., 2019; Niemeläinen et al., 2017; Singh et al., 2019). The majority of patients undergoing elective TKR surgery have a background of osteoarthritis (OA) (Briggs et al., 2016). These patients present knee-related symptoms preoperatively, such as pain, and reduced physical function (Hunter & Bierma-Zeinstra, 2019). Pain and discomfort together with a possible fear of movement or avoidance of physical activity (PA) after TKR surgery may challenge rehabilitees especially with independent exercising after their discharge from the hospital (Brown et al., 2020). Therefore, it is important to provide these individuals with new rehabilitation methods, such as exergaming, that can meet these challenges and support their rehabilitation in a way that might increase their commitment to exercise and thus, help them achieve better physical performance in a quick manner.

The present study had two main purposes: 1) to investigate the feasibility of exergames in post-TKR management in older adults, and 2) to investigate the effect of exergame-based intervention on the physical function and pain in older adults, especially after TKR. The feasibility was assessed as the movement characteristics during exergaming using exergames custom-made for post-TKR rehabilitation. The effects of exergaming were evaluated with several rehabilitation outcomes characterizing physical function and pain, including walking and mobility, lower-extremity function, and knee-related symptoms compared with other type of exercise or no exercise.

2 REVIEW OF THE LITERATURE

2.1 Older adults undergoing total knee replacement surgery

OA of the knee is globally one of the significant threats to healthy aging and one of the leading and growing causes for ending up with a TKR (Briggs et al., 2016; Niemeläinen et al., 2017; Singh et al., 2019). Knee OA is a chronic and degenerative joint disease where the most typical symptoms are pain, stiffness, and instability in the affected knee joint and reduced physical function (Hunter et al., 2008). When conservative treatment does not decrease the pain and other symptoms, the functional ability is substantially impaired, and the quality of life is significantly reduced, surgical treatment is considered (Hunter & Bierma-Zeinstra, 2019). After a recent TKR operation, therapeutic exercise is essential to decrease the symptoms and sedentary behavior and increase and improve declined functional performance (Artz et al., 2015; J. Lee et al., 2015; Skou et al., 2015)

2.1.1 Effect of total knee replacement surgery on the functional ability

The physical function together with cognitive and social function form the functional status of an individual, which refers to the ability of the individual to do basic physical and cognitive activities and participate in life situations (National Committee on Vital and Health Statistics, 2001). In other words, functional ability is the interaction between the physical and mental capacities of individuals and their environments that enable the individual to be and to do what is important and meaningful to them (World Health Organization, 2015). When health conditions, such as OA, exerts effects on the functional ability of a person, it may pose barriers, for example, in walking, transferring, or participation in leisure time PA, or activities in daily errands and commuting. The functional ability may be monitored and assessed both objectively and subjectively. The typical tests and questionnaires used for older adults with OA or for those who have already undergone TKR are, for example, the Timed Up and Go (TUG) test (Christopher et al., 2021) and Oxford Knee Score (OKS) questionnaire (Reito et al., 2017). The former assesses the mobility, and the latter assesses an individual's level of function, activities of daily living, and perceived pain.

During the first weeks after TKR surgery, there is a noticeable decrease in the physical function in terms of the knee range of motion and muscle strength of the operated lower limb and motor function compared with the pre-operative level (Bade et al., 2010; Mizner et al., 2005). Moreover, the knee related pain increases (E. Y. Chan et al., 2013). The pain and discomfort experienced in the first weeks after surgery may be the main reasons why people with knee OA continue sedentary behavior that is already characteristic for this patient group preoperatively (Powell et al., 2021). Moreover, a fear of physical movement and avoidance of PA may contribute to sedentary behavior after a TKR (Brown et al., 2020). This might be a challenge for the realization of postoperative therapeutic exercise, which is typically started no later than the day after surgery under the guidance of the hospital's physiotherapist. Rehabilitative goals should include improvements in functional independence, mobility, and knee range of motion (ROM), normalization of walking, and reduction in knee-related pain (Mistry et al., 2016). With an improvement in knee-related symptoms and functionality, such as knee extension and increased flexion strength and mobility, it is possible to restore the functional ability of patients with TKR to at least the pre-surgery level and even more.

2.1.2 Therapeutic exercise after total knee replacement surgery

Therapeutic exercise in physical rehabilitation is systematically implemented exercise or training, which is planned and instructed by rehabilitation professionals, such as a physiotherapist, and aims to uphold and enhance the functional ability and well-being of the rehabilitee (Babatunde et al., 2017; Pasanen et al., 2017). The exercise instructions may be verbal, or they can be given, for example, on paper or with a smartphone application. Therapeutic exercise may be implemented in supervised group sessions or individually arranged sessions in rehabilitation or community-based premises, like outpatient physical therapy clinics or retirement homes (Artz et al., 2015). Moreover, therapeutic exercise may be implemented in the rehabilitees' homes as an independent exercise or in such a way that a physiotherapist is guiding on-site or remotely (Artz et al., 2015).

To achieve rehabilitative goals in post-TKR therapeutic exercise, it should comprise knee extension and flexion range of motion (ROM) and muscle strength exercises and motor function exercises, such as walking and balance exercises (Jette et al., 2020). It has been observed that knee extension ROM exercises started shortly after surgery especially have a significant effect on the mobility in a knee joint and the smoothness of walking (Kubota et al., 2022). Similarly, strengthening exercises, especially on the knee extensor muscles exert a substantial effect on the recovery of motor function (Capin et al., 2022). Muscle strength exercises are equally important for both the operated and non-operated lower limb (Capin et al., 2022; Suh et al., 2019). Moreover, balance exercises contribute to the walking performance in addition to balance-specific performance (Doma et al., 2018).

There is a lack of detailed description of the recommended exercise dosage (Bakaa et al., 2021) in terms of the exercise volume and intensity; however, post-TKR therapeutic exercise may follow the exercise recommendation for older adults with OA (Katz et al., 2001; Kolasinski et al., 2020). Flexibility and strengthening exercises should be performed daily, the former from 1 to 5 and the latter from 1 to 15 repetitions depending on the intensity (low, moderate, and high). In addition, endurance training should be performed 20 to 30 minutes per day 3 to 5 times a week. The progression can be adjusted by adding or changing exercises or by changing the volume and intensity of exercises. The benefits of post-TKR therapeutic exercise for physical function, such as mobility and walking, and pain can be seen at three months after surgery and beyond (Bade et al., 2010).

It has been suggested that outpatient physical therapy after a TKR surgery leads to more rapid recovery (Christensen et al., 2020). However, home-based rehabilitation after a TKR surgery has been found to be an appropriate first line of therapy (Artz et al., 2015; Buhagiar et al., 2019). When therapeutic exercise is the patient's responsibility at home after discharge from hospital, it is important to ensure sufficient exercising volume. New exercising methods, such as exercise games, i.e., exergames, may contribute to independent training at home and thus, improve the potential effectiveness of the postoperative rehabilitation of patients undergoing TKR.

2.2 Exergames

Gamified exercises, exergames, are one manifestation of gamification or serious games. The former refers to "the use of game design elements in non-game contexts" and the latter entails the use of a game for a purpose other than entertainment (Deterding et al., 2011). The idea in exergames is to use the features of entertainment games, such as rewards, leader boards, levels, and self-representation with avatars, to enhance and encourage the user to perform activities for achieving the desired outcomes (Matallaoui et al., 2017).

The term exergame is a combination of the terms physical exercise and active video game. Physical exercise is a planned, structured, and repetitive bodily activity to maintain or improve the health and function (Caspersen et al., 1985), while an active video game requires repetitive bodily movements from the player to progress through the game. An interaction between the exergame and the player is formed through a motion tracking system and the storyline of the game (Kato, 2010). In exergames, the motion tracking system may be, for example, camera-based (Fitzgerald et al., 2006). The camera follows the movements of the player and transmits biomechanical biofeedback as input to the game interface for control of gameplay, and feeds it back to the player via graphical animation, i.e., as an avatar that replicates the player's movements on the screen (Giggins et al., 2013). The storyline of the game guides a player to the goal of the game, that is the movement, i.e., exercise, to be performed for the duration of the game (Deterding et al., 2011; Matallaoui et al., 2017). The story can be, for example, picking vegetables in the garden, which is performed in the game by doing squatting exercises. By following the storyline of the game while controlling the game's avatar with bodily movements, the player is immersed in the gameplay and contributes to the progress and results of the game, possibly without noticing the burden of repetitive activity (Gokeler et al., 2016), such as a series of squat movements as mentioned above.

Indeed, one aim of using exergames in leisure time or in physical rehabilitation is that exergames may offer an entertainment and visual and audio reward from performance, and thus, enhance enjoyment and possibly be more appealing and a preferred form of exercise (van der Kooij et al., 2019). This is an important aspect in physical rehabilitation as it may encourage the rehabilitee's adherence to exercise and, consequently, increase the exercise volume and improve the potential effect on the physical function of the individual (Suleiman-Martos et al., 2022). However, there is still a contradiction with previous research. Some research results have shown that older adults may feel more motivated and show higher adherence with therapeutic exercise using exergames (Alves da Cruz et al., 2022; Pacheco et al., 2020; Suleiman-Martos et al., 2022). However, the results also show that exergaming in older adults would not be more adherent, enjoyable, and motivating compared with more traditional ways to perform exercise (Oesch et al., 2017).

The majority of exergames are commercially available, such as Wii (Nintendo, Japan), PlayStation (Sony, Japan), or Xbox (Microsoft, USA). These games are used for leisure time entertainment, but are also widely used in the studies investigating the feasibility (de Vries et al., 2018; Willaert et al., 2020) and effects of exergaming on physical rehabilitation in older adults (Hai et al., 2022; Reis et al., 2019; Suleiman - Martos et al., 2022). In addition, customized exergames, i.e., games that may have been mainly developed for a specific group of rehabilitees and rehabilitative needs (Pirovano et al., 2016), have been studied with respect to physical rehabilitation in older adults, although lesser than commercially available exergames (Suleiman-Martos et al., 2022). In both cases, in commercially available and customized exergames, the development of the player's gaming skills or the exercise progression in rehabilitation can be considered (M. Lee et al., 2016; Skjæret et al., 2016). For example, a player may automatically proceed to a higher level of the game after successful performance (Uzor & Baillie, 2019), or the exercise traits, such as the number of repetitions in the games or the number of games in the session (Stanmore et al., 2019) or the duration of the game (Delbroek et al., 2017) may be increased gradually.

While exergaming, the player receives visual and/or audio instructions and feedback in an active video game to ensure that the intended and correct performance of the exercise is conducted (Rutkowski et al., 2019; Yeşilyaprak et al., 2016). For example, the gaming system may display an alert message when the performed movement, such as a squat, does not achieve the aimed ROM (Sato et al., 2015), or when the repetition rate during the performed movement does not remain on the aimed pace (Doyle et al., 2011). In addition, for example, an audio signal may be given in both cases.

2.3 Therapeutic exercise exploiting exergames in older adults

Therapeutic exercise exploiting commercially available and customized exergames has come to be more popular in physical rehabilitation in older adults as their effect on physical function has been reported to be good (Reis et al., 2019; Taylor et al., 2018). Exergames selected to be used in rehabilitation, adherence to exergaming, and the absence of adverse events during exergame-based rehabilitation may be factors that could contribute to the effectiveness of training, for example, on physical function and pain (Altorfer et al., 2021; Skjæret et al., 2016), and are therefore important issues to be investigated alongside the effectiveness study.

2.3.1 Feasibility of exergames

The feasibility of exergame-based training can be evaluated with the kinematics during exergame performance. This means that when assessing the kinematics during exergame performance, there is an interest in whether the player could achieve exercise requirements in terms of the movement characteristics as the volume, range, and intensity of movement.

To best of our knowledge, the range of movement during the performance in the exergame has not yet been studied. However, studies investigating the volume of movement (Skjæret-Maroni et al., 2016) and the intensity of movement (de Vries et al., 2018; Skjæret-Maroni et al., 2016; Willaert et al., 2020) in older adults exist. Interest has been in the difference in the volume or intensity of movement during the performance while using commercial exergames (de Vries et al., 2018; Skjæret-Maroni et al., 2016) and while using the customized exergame and the commercial exergame (Willaert et al., 2020). In studies, the intensity of movement was evaluated through repetitions, center of mass displacement, or muscle activity levels in several movements (stepping, weight shifts, and squats). The studies showed that the same exergame with different gaming velocities or levels of difficulty, or different exergames with similar exercise, be they commercially available or customized, may challenge the volume and intensity of movement at very different levels.

2.3.2 Adverse events and adherence during exergaming

Adverse events are harms, by which the possible causal relationships with ongoing intervention are assessed. These may be, for example, accidental falls during exergaming or muscle pain during or after exergaming, i.e., may be related to undertaking exercises performed using exergame(s) (Bacha et al., 2018; Prosperini et al., 2021). Adverse events may be identified using, for example, diaries filled out by the participants (Gschwind et al., 2015), or the data documented by research personnel based on the reporting by participants (Prosperini et al., 2013), or on their own observations (Altorfer et al., 2021). Adverse events can be classified, for example, from mild to severe and based on the classification define actions taken, such as reduction or suspension of training for a specified period (Prosperini et al., 2013).

In older adults during exergaming, reported adverse events has been related, for example, to fatigue, low back pain, knee pain, or delayed muscle pain. Occurrences have been reported, for example, after the first session only (Bacha et al., 2018; Gomes et al., 2018) or after the performance of the most challenging exergames (Prosperini et al., 2013). Additionally, pain during exergaming has been reported also as reason for dropping-out from intervention (Oesch et al., 2017). However, there are also studies where exergame-related adverse events did not occur during the intervention (Altorfer et al., 2021; Gschwind et al., 2015; Pournajaf et al., 2022).

The adherence to exergaming refers to the commitment to participate in offered exergaming sessions (Segura-Ortí et al., 2019) or to follow the given instructions of exergaming dose, such as exergaming three times a week at home for the duration of intervention (Uzor & Baillie, 2019). Adherence can be defined, for example, through dropouts or pre-defined cut-off values, such as attendance to a minimum of 80% of the intervention sessions, or through attended sessions or how the training has been realized in relation to what was planned (Bakaa et al., 2021; Pournajaf et al., 2022). To measure the adherence, self-reported diaries, questionnaires, and digital logs, for example, can be used (Zhang et al., 2022). In addition, the games could enable automatic data collection on adherence to the rehabilitative intervention (Jansson et al., 2022).

The use of technology, enjoyment, and absence of unpleasant experiences are the key factors that may increase the adherence to exercise (Collado-Mateo et al., 2021). The adherence to supervised training is observed to be high, 75% and over (Pacheco et al., 2020; Suleiman-Martos et al., 2022); however, it has been found to remain low in unsupervised, independent training, even lesser than 5% when full adherence to the exercise program was assessed (Simek et al., 2012). When evaluating the adherence to unsupervised, exergame-based exercise programs, high adherence has been observed (Valenzuela et al., 2018). Therefore, exergame-based training may have the potential to increase PA, for example, in independent training performed after TKR surgery (Sašek et al., 2021). However, it should be noted that unsupervised exergame-based training in older adults has been little studied and may therefore cause bias in assessing adverse events and adherence (Howes et al., 2017; Skjæret et al., 2016; Valenzuela et al., 2018).

2.3.3 Effect of exergaming on physical function and pain

When exploring the effect of exergame-based interventions on physical function, studies have shown promising effects on several domains. Exergaming has been more or equally effective on mobility (Pacheco et al., 2020; Perrochon et al., 2019; Suleiman‐Martos et al., 2022; Taylor et al., 2018), balance (Cano Porras et al., 2018; Hai et al., 2022; Pacheco et al., 2020; Suleiman‐Martos et al., 2022; Taylor et al., 2018), upper or lower body muscle strength (Hai et al., 2022; Suleiman‐Martos et al., 2022; Taylor et al., 2018), walking (Cano Porras et al., 2018; Hai et al., 2022; Suleiman‐Martos et al., 2022), and aerobic endurance (Hai et al., 2022; Suleiman-Martos et al., 2022) when compared with active or inactive comparison groups. Similarly, exergaming has demonstrated improved balance and walking in studies comparing the results measured before the intervention with the results after the intervention (Ismail et al., 2022).

A considerable part of older adults studied in exergame studies are healthy or community-dwelling (Hai et al., 2022; Ismail et al., 2022; Pacheco et al., 2020; Suleiman-Martos et al., 2022; Taylor et al., 2018) or with neurologic disorders, such as stroke and Parkinson's disease (Cano Porras et al., 2018; Ismail et al., 2022; Perrochon et al., 2019). In addition, in studies of participants without neurologic condition, the obtained significant results have been more on the effect of exergaming on balance and mobility, than on walking. The duration of the exergame-based interventions varies between 2 and 24 weeks, but are mainly 2 or 3 months (Hai et al., 2022; Perrochon et al., 2019; Taylor et al., 2018). During the intervention period, the participants have an exergame session for approximately 30 to 45 minutes per session on average three times a week (Hai et al., 2022; Perrochon et al., 2019). Moreover, in these studies, exergame-based interventions have been mainly supervised and not implemented at participants' homes.

Recent systematic reviews on exergaming in patients with TKR, which combined the results of RCT studies using biofeedback with and without gamification, show that subjective physical function and pain was significantly enhanced in the intervention group compared with the control group within one month (Peng et al., 2022) and at 12 weeks and at 6 months (Gazendam et al., 2022) postoperatively. Another recent study, an RCT comparing exergaming with conventional physiotherapy in older adults with OA, showed more positive decrease in pain in participants who exergamed (Mete & Sari, 2022). Otherwise, there seems to be little recent research focusing on the effect of exergaming on pain in older adults despite the positive results observed earlier (Stanmore et al., 2019).

2.3.4 Current literature on exergaming after total knee replacement

A systematic search of the current literature on employing exergames in physical rehabilitation in older adults undergoing TKR surgery was conducted in August 2022 in the following databases: Medline Ovid, Cochrane Central Register of Controlled Trials, Database of Systematic Reviews, and PEDro. A total of 125 references were identified from the databases. A study selection was conducted using the PICOS criteria (Patients, Intervention, Comparison group, Outcomes, Study design) (McKenzie et al., 2022; Rios et al., 2010): patients undergoing TKR surgery (Patients), therapeutic exercise employing exergames (i.e., biofeedback with gamification) (Intervention), none or other type of exercise (Comparison group), any outcome (Outcomes), and all but reviews (Study design). In addition, two publications were identified through a citation search and were included in the review. The search strategy, study selection, and excluded (n=17) studies with justification are presented in appendix 1.

Eight studies were included in the review: seven RCTs (Christiansen et al., 2015; Fung et al., 2012; Hadamus et al., 2021; Hardt et al., 2018; Jin et al., 2018; Pournajaf et al., 2022; Yoon & Son, 2020) and one case report (Hong & Lee, 2019) (TABLE 1). The studies were conducted in Europe (Hadamus et al., 2021; Hardt et al., 2018; Pournajaf et al., 2022), in North-America (Christiansen et al., 2015; Fung et al., 2012), and in Asia (Hong & Lee, 2019; Jin et al., 2018; Yoon & Son, 2020). A total of 17 studies were excluded at full text screening due to wrong (n=16) or ambiguous (n=1) interventions. The majority of studies that were excluded because of wrong interventions used biomechanical biofeedback without gamification (n=13). The overall risk of bias (Sterne et al., 2019) in the included RCTs was as follows: 14.3% low, 57.1% some concern, and 28.6% high (Appendix 1).

In the included studies, the participants' (n=331) age ranged from 62 to 72 years; the majority of participants were women. In one study (Fung et al., 2012), the clinical background of the participants was not reported, in other studies, the participants were patients with knee OA. Four studies (Christiansen et al., 2015; Hong & Lee, 2019; Jin et al., 2018; Pournajaf et al., 2022) reported that TKR was performed unilaterally, and one study (Yoon & Son, 2020) reported that the TKR was performed bilaterally.

In all the studies, the exergaming intervention was implemented after the TKR surgery. In one study (Jin et al., 2018), the duration of the intervention was not reported. In Hardt et al. (2018), the intervention was conducted during the hospital stay with a mean duration of 7 days in the intervention group and in the control group. In other studies, the duration of interventions ranged from 53 to 54 days (Fung et al., 2012) or from 2 to 6 weeks (Christiansen et al., 2015; Hadamus et al., 2021; Hong & Lee, 2019; Pournajaf et al., 2022; Yoon & Son, 2020). Two studies had follow-up periods ranging from 2 (Yoon & Son, 2020) to 20 (Christiansen et al., 2015) weeks. In all studies, exergaming was adjunct to a standard rehabilitation procedure. In addition, in two studies (Fung et al., 2012; Pournajaf et al., 2022), the control group had an additional lower extremity or balance exercises for the same duration as exergaming in the intervention group. In six studies, all training was supervised (Fung et al., 2012; Hadamus et al., 2021; Hong & Lee, 2019; Jin et al., 2018; Pournajaf et al., 2022; Yoon & Son, 2020). In the study of Hardt et al. (2018), standard rehabilitation was supervised; however, adjunct exergaming in the intervention group was performed independently. Only in one study (Christiansen et al., 2015), standard exercising and exergaming were performed independently and, in addition, at the participants’ home. Customized exergames were used in five studies (Christiansen et al., 2015; Hardt et al., 2018; Jin et al., 2018; Pournajaf et al., 2022; Yoon & Son, 2020) while other studies (Fung et al., 2012; Hadamus et al., 2021; Hong & Lee, 2019) used commercially available games. One study (Pournajaf et al., 2022) reported that participants had no adverse events during exergame sessions.

Three studies (Christiansen et al., 2015; Hardt et al., 2018; Pournajaf et al., 2022) reported on the adherence to exergaming and exercising. One of them (Hardt et al., 2018) reported on adherence in the intervention group, while others reported on adherence in both groups. In the study of Christiansen et al. (2015), the participants were instructed to perform exergaming once daily and standard exercise once daily in the intervention group and standard exercising twice daily in the control group. After the intervention period, the mean sessions per day were 0.8 times exergaming and 1.8 times standard exercising in the exergame group, and 1.8 times standard exercising in the control group (Christiansen et al., 2015). The attendance percentages in the study of Pournajaf et al. (2022) were 96.6% in the intervention group and 100% in the control group. The mean session times during hospital stays was 14 (Hardt et al., 2018), and the correlation to the given instruction (3 to 5 times a day) was not reported.

The outcomes in the included studies measured the pain and physical function as, for example, walking (Christiansen et al., 2015; Fung et al., 2012; Hardt et al., 2018; Hong & Lee, 2019; Pournajaf et al., 2022; Yoon & Son, 2020), balance (Fung et al., 2012; Hadamus et al., 2021; Hong & Lee, 2019; Pournajaf et al., 2022; Yoon & Son, 2020), knee ROM (Fung et al., 2012; Hardt et al., 2018; Jin et al., 2018), and lower limb muscle strength (Christiansen et al., 2015; Hardt et al., 2018; Hong & Lee, 2019; Pournajaf et al., 2022). Several tests and questionnaires, such as TUG and Western Ontario and McMaster University osteoarthritis index (WOMAC) (McConnell et al., 2001) were used. The studies compared the preoperative (Christiansen et al., 2015; Hardt et al., 2018; Hong & Lee, 2019; Jin et al., 2018) or postoperative level (Fung et al., 2012; Hadamus et al., 2021; Pournajaf et al., 2022; Yoon & Son, 2020) to that after the intervention. In studies with RCT design, the physical function increased significantly in five studies (Christiansen et al., 2015; Hardt et al., 2018; Jin et al., 2018; Pournajaf et al., 2022; Yoon & Son, 2020) and pain decreased significantly in two studies (Hardt et al., 2018; Jin et al., 2018), favoring the intervention group. Significance in the physical function was observed in tests measuring the lower limb muscle strength (Christiansen et al., 2015), knee ROM (Hardt et al., 2018; Jin et al., 2018), walking (Pournajaf et al., 2022), and balance (Yoon & Son, 2020), and in questionnaires measuring knee-related symptoms, and physical ability (Hardt et al., 2018; Jin et al., 2018). In addition, in the case study (Hong & Lee, 2019), exercise increased the muscle strength and proprioception of the lower limbs of the participant, and restored the balance and gait, which were impaired after surgery, to the pre-surgery level. Moreover, Fung et al. (2012) and Hardt et al. (2018) collected data on the length of participants' interventions, which was not the same for all the participants, i.e. constant, such as two weeks, and Fung et al.

(2012) gathered the satisfaction with therapy services. There were no significant between-group changes in these outcomes.

TABLE 1 Description of studies employing exergames in rehabilitation after total knee replacement.

Study	Participants	Intervention		Technology	Adherence	Outcomes	Main findings
		Duration	Main content (Implementation)				
Christiansen et al. 2015, USA RCT	IG; n=13, Age 68 y, Male 54% CG; n=13, Age 67 y, Male 46%	6 weeks with 20 weeks follow-up	IG and CG; Standard home exercise program (I) IG; Additional Wii gaming (I)	Nintendo Wii Fit Plus games, Wii Balance Board	IG and CG; Number of performed training sessions	Weight-bearing ratio, Functional performance (FTSST), Gait speed, Hip, knee, and ankle joint moments	Significant difference in functional performance favoring the IG.
Fung et al. 2012, Canada RCT	IG; n=27, Age 68 y, Male 47% CG; n=23, Age 68 y, Male 53%	IG; Mean 54.2 days CG; Mean 53.0 days	IG and CG; Physical therapy session (S) IG; Additional Wii Fit gaming (S) CG; Additional lower extremity exercise (S)	Nintendo Wii Fit games, Wii Balance Board	NR	Knee ROM, Walking (2MWT), Pain (NPRS), Lower extremity function (LEFS), Balance (ABCS), Length of outpatient rehabilitation, Patient satisfaction with therapy services	No significant between group difference in any outcomes.
Hadamus et al. 2021, Poland RCT	IG; n=21, Age 69 y, Male 33% CG; n=21, Age 68 y, Male 33%	4 weeks	IG and CG; Standard stationary rehabilitation (S) IG; Additional VR games (S)	Virtual Balance Clinic prototype system (games, balance plate, Kinect 2 camera)	NR	Postural stability	No significant between group difference in outcome.

(Continues)

TABLE 1 Continues

Study	Participants	Intervention		Technology	Adherence	Outcomes	Main findings
		Duration	Main content (Implementation)				
Hardt et al. 2018, Germany RCT	IG; n=33, Age 66 y, Male 15% CG; n=27, Age 69 y, Male 11%	IG; Mean 6.6 days CG; Mean 6.9 days	IG and CG; Standard rehabilitation and pain management (S) IG; Additional knee extension exercise using game application (I)	A prototype of GenuSport Knietrainer and smart tablet with GenuSport application	IG; Number of performed training sessions	Active and passive knee ROM, Pain (NRS), Muscle strength (knee extension), Motor performance (TUG, 10-MWT, 30s STS Symptoms and functional ability related to knee (KOOS, KSS), Length of hospital stay	Significant difference in active ROM, pain in motion, and knee-related symptoms and functional ability (KSS) favoring the IG.
Hong & Lee 2019, South Korea CR	n=1, Age 62 y, Female	2 weeks	Conventional physical therapy and additional VR gaming (S)	PlayStation 4Pro games, Head-mounted display	NR	Muscle Strength (STS), Proprioception, Balance (BBS), Gait (10-MWT)	Increase in muscle strength (32%) and proprioception (45%). Balance and Gait recovered to pre TKR level

(Continues)

TABLE 1 Continues

Study	Participants	Intervention		Technology	Adherence	Outcomes	Main findings
		Duration	Main content (Implementation)				
Jin et al. 2018, China RCT	IG; n=33, Age 66 y, Male 46% CG; n=33, Age 66 y, Male 39%	NR	IG and CG; Passive knee flexion exercise (S) IG; Additional knee flexion exercise using VR game (S)	Customized VR game, Head-mounted display	NR	Symptoms and functional ability related to knee (WOMAC, HSS), Pain (VAS), Knee ROM, Days needed for knee ROM to reach 60° and 90°	Significant difference favoring IG in WOMAC and HSS at 1, 3, and 6 months, in pain at 3, 5, and 7 days, in knee ROM at 3, 7, and 14 days after TKR. Days needed were significantly lower in the IG.
Pournajaf et al. 2022, Italy RCT	IG; n=29, Age 68 y, Male 14% CG; n=27, Age 71 y, Male 8%	3 weeks	IG and CG; Conventional rehabilitation (S) IG; Additional balance training using SGs (S) CG; Additional balance exercises (S)	Customized non-immersive VR-based SGs with biofeedback (Virtual Reality Reha-bilitation System [VRRS])	IG and CG; Percentage of performed training sessions	Functional mobility, Dynamic balance, and Walking ability (TUG), Walking speed (10-MWT), Lower-extremity muscle strength (MRC), Pain (VAS), Independence in ADL (mBI), Spatiotemporal and joint kinematic gait parameters	Significant difference favoring IG in temporal parameters: stance time of the affected limb

(Continues)

TABLE 1 Continues

Study	Participants	Intervention		Technology	Adherence	Outcomes	Main findings
		Duration	Main content (Implementation)				
Yoon & Son 2020, South Korea RCT	IG; n=15, Age 72 y, Male 0% CG; n=15, Age 72 y, Male 0%	2 weeks (+ 2 weeks follow-up)	IG and CG; Exercise therapy (S) IG; Additional gamified balance exercise in different surfaces (S)	VR glasses, BASEjump VR Wingsuit Application	NR	Static and dynamic balance, Gait ability (TUG), Symptoms and functional ability related to knee (WOMAC)	Significant differences in static and dynamic balance favoring the IG.

Implementation: I = Independent training, S = supervised (guided) training
CR = case report, RCT = randomized controlled trial
CG = Control Group, IG = Intervention group
NR = not reported, SG = serious games, VR = virtual reality
2MWT = two minutes walking test, 10-MWT = ten-meter walking test, ABCS = Activity-specific Balance Confidence Scale, ADL = activities in daily life, BBS = Berg balance scale, FTSST = five time sit to stand test, HSS = Hospital for Special Surgery knee score, KOOS = Knee Injury and Osteoarthritis Outcome Score, KSS = Knee Society Score, LEFS = Lower Extremity Functional Scale, mBI = modified Barthel Index, MRC = Medical Research Council scale, NPRS = numeric pain rating scale, NRS = numeric rating scale, ROM = range of motion, STS = sit to stand test, TKR = total knee replacement, TUG = Timed Up & Go test, VAS = visual analog scale, WOMAC = Western Ontario and McMaster University osteoarthritis index

2.4 Summary of the literature

In summary, the review of literature reveals that there is a limited understanding on the feasibility of exergames in rehabilitation and its effects on the physical function and pain in older adults without neurological conditions and particularly during post-TKR rehabilitation.

Few studies have investigated the feasibility from the perspective of kinematics during exergame performance by comparing commercially available games or by comparing customized games with commercially available games. There has been interest in the volume and intensity of movement, how those had been realized during exergaming, and how they differ between games. However, investigation of the range of movement during exergaming and the comparison of all mentioned movement characteristics (i.e., the volume, range, and intensity of movement) between exergaming and standard exercise are lacking. Such research is needed to validate the use of exergame-based therapeutic exercise in studies that evaluated its effectiveness on the study outcomes, such as physical function and pain. In other words, such research is required to ensure the feasibility of an exergame-based intervention with games, which best matches the therapeutic exercise requirements of the rehabilitation being studied.

The effect of exergaming on physical function, in general, has been studied in older adults who are healthy or community-dwelling, or in older adults who have neurologic conditions, such as stroke. The main interest in the studies exploring the effect of exergame-based interventions on physical function has been on its effect on improving balance. In addition, little research has been carried out on the effect of exergaming on pain, although it has been found to have a positive effect on pain reduction, for example, in patients with OA. Moreover, exergame-based interventions have been short with duration, mostly supervised and biofeedback has been used, but without gamification. There is a gap in the knowledge of the effect of long-term home interventions comparing the preoperative physical function and pain to postoperative levels when exergaming is the primary form of exercise after surgical treatments, such as TKR.

3 PURPOSE OF THE STUDY

The purpose of this thesis was to investigate the feasibility of exergames in exergame-based rehabilitation and the effects of exergame-based rehabilitation on physical function and pain in older adults, especially after TKR. The specific research questions were:

1) Do patients with TKR achieve similar movement characteristics with customized exergames as achieved in the standard post-TKR exercises? (Study I)

2) Does exergame-based training improve walking in older adults who did not have neurological disorders compared with no exercise or other exercise? (Study II)

3) Does the participants' age or baseline walking performance, interventions' characteristics (i.e., duration of intervention, setting of intervention, number of sessions per week, duration of single session, type of comparison group, and technology used), or risk of bias explain the effectiveness of exergame-based training on walking? (Study II)

4) Does customized home-based exergaming for a duration of four months have an effect on knee related physical function and pain in older adults after unilateral TKR surgery compared with standard protocol exercising? (Study III)

4 RESEARCH METHODOLOGY

4.1 Study design

This thesis is based on the data of Business Ecosystems in Effective Exergaming project and three original publications (Study I-III) (TABLE 2). Ethical approvals were given to the Study I from the Ethics Committee of the Central Finland Health Care District (record number 4U/2018) and to the Study III from the Ethics Committee of the Southwest Finland Health Care District (record number ETMK 66/2018). Studies I and III received hospital research permission from hospitals in where the recruitment took place, i.e., the Turku University Hospital (Study III) in Turku and the Central Finland Hospital Nova (former Central Finland Central Hospital) in Jyväskylä (Studies I & III). The recruited participants in Studies I and III provided written informed consent prior to enrolment.

TABLE 2 Summary of the studies included in the thesis.

Study	Study design	Participants	Exercise/Exergaming	Comparison group	Duration of intervention	Primary outcomes	Secondary outcomes	Other outcomes
I	Cross-sectional feasibility study	Older adults aged 60-75 years with TKR	i) Single bout of standard post-TKR exercise ii) Customized post-TKR exergaming	N/A	N/A	Movement characteristics	Perceived exertion and knee pain	N/A
II	Systematic review and meta-analysis with meta-regression	Older adults aged 60 years and older with no neurological disorders	Exergaming intervention	Other type or exercising or no exercising	2 to 26 weeks	Walking	N/A	N/A
III	Dual-center RCT	Older adults aged 60-75 years with TKR	Customized post-TKR exergaming intervention	Standard post-TKR exercise	4 months	Knee-related physical function and pain, mobility	Walking, Knee joint ROM, Lower extremity performance, Muscle strength, Knee pain	Satisfaction with the operated knee, Adherence, Adverse events, PA

N/A = Not applicable, PA = physical activity, RCT = randomized controlled trial, ROM = range of motion, TKR = total knee replacement

A cross-sectional feasibility study (Study I, later *feasibility study*) evaluated the usability of customized exergames for post-TKR rehabilitation and utilized those results in the Study III. The study investigated the movement characteristics performed during weight shifting exergames and knee extension-flexion and squatting exergames and compared the latter with corresponding movement characteristics in standard post-TKR exercises. Before a maximum of four months had passed since the TKR surgery, the participants attended a single two-hour test session in the exercise laboratory during which all the measurements related to the study were taken.

The systematic review and meta-analysis with meta-regression (Study II, later *systematic review*) was registered (CRD42020148701) in the International Prospective Register of Systematic Reviews. The eligibility criteria were defined utilizing the PICOS framework (Participants, Intervention, Comparison group, Outcome, Study design). The study described and pooled the data from previously published RCTs (Study design) evaluating the effect of exergaming (Intervention) on walking (Outcome) compared with no exercise or other type of exercise (Comparison group) in older adults who did not have neurological conditions (Participants). A systematic literature search was conducted with no language or publication date restrictions.

The 4-month non-blinded, dual-center, parallel group RCT (Study III, later *dual-center RCT*) was registered at ClinicalTrials.gov (NCT03717727). Older adults who were scheduled to undergo TKR surgery and voluntarily participated in the study were randomly assigned to either the intervention or control group. This study compared home-based exergaming (intervention group) with the home-based standard exercising (control group) on knee related pain and physical function after the TKR. The outcome assessments were performed at three timepoints; the baseline assessment before TKR surgery, and at the 2- and 4-month follow-up assessments after TKR surgery (FIGURE 1). The timeline of the study from the beginning of recruitment to the 4-month evaluation of the most recent recruited participant is presented in FIGURE 2.

In the dual-center RCT (Study III), the COVID-19 pandemic caused a deceleration in the recruitment and deviations in exercise laboratory measurements. Due to this, the intended sample size was not achieved, and the physical performance measurements were not assessed in all the participants at the 2- or 4-month follow-ups.

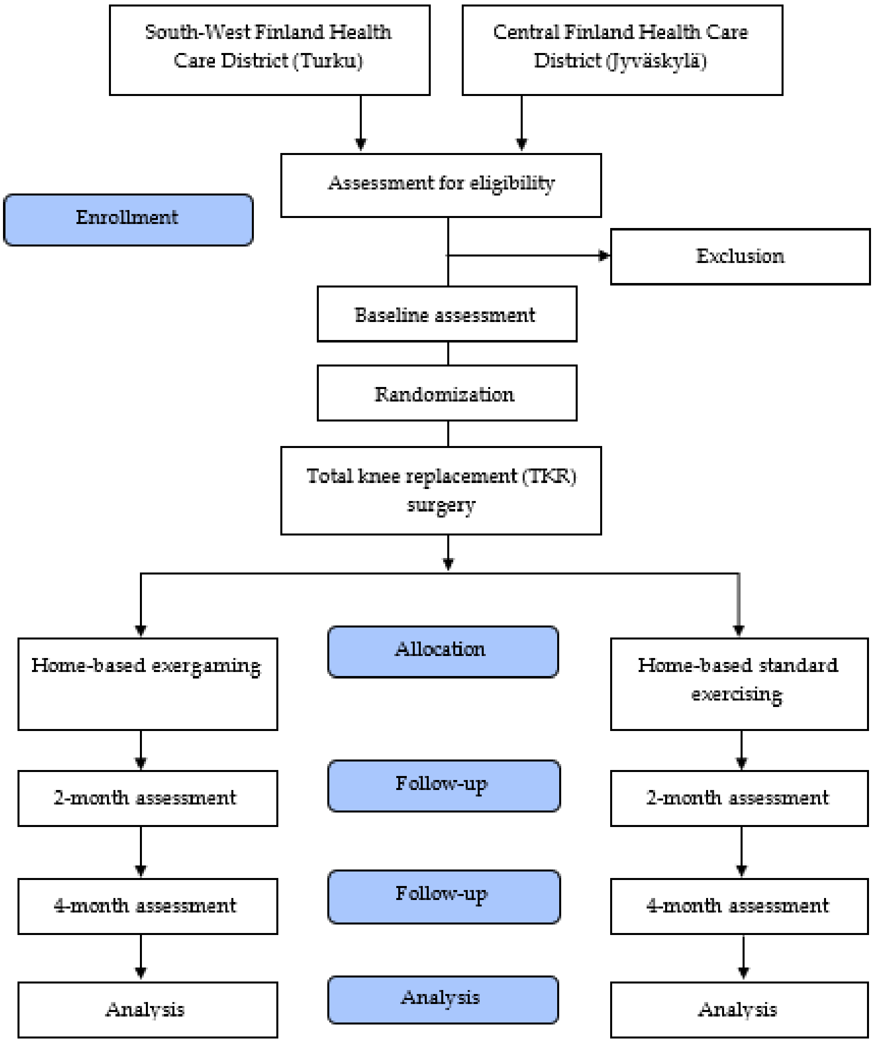

FIGURE 1 The flow chart of the dual-center randomized controlled trial (Study III).

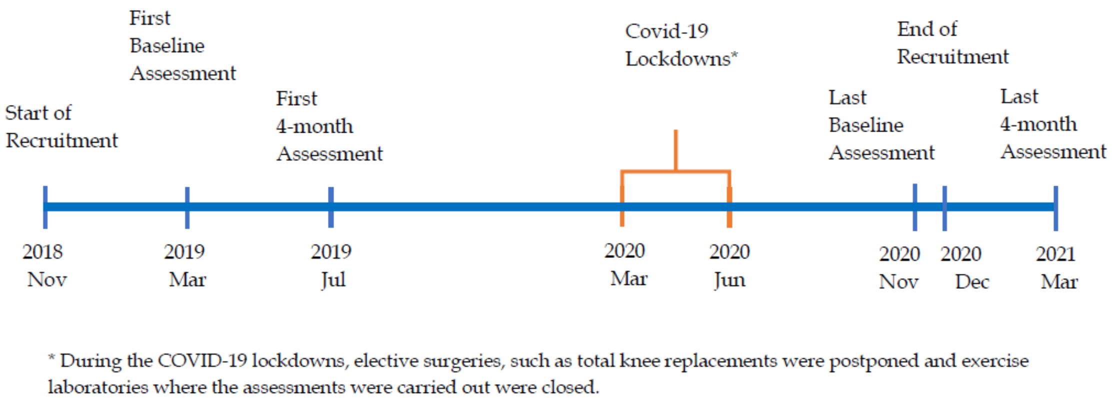

FIGURE 2 The timeline of the dual-center randomized controlled trial (Study III).

4.2 Participants

Individuals undergoing TKR were recruited from the Central Finland (Studies I & III) and the Southwest Finland (Study III) Health Care Districts during the preoperative (Studies I & III) or postoperative (Study I) hospital outpatient visits. For the participants, either a decision had been made regarding the surgery (Studies I & III) or a maximum of three months had passed since the surgery (Study I).

The eligibility criteria of the participants in all the studies (I-III) are presented in TABLE 3. In addition, in the Studies I and III, voluntary patients had to have normal vision with or without eyeglasses, and they were asked if they had unreasonable shortness of breath or chest pain during exercise or other physical exertion, or seizures of unconsciousness, fainting or dizziness, or heart medication to ensure safe physical testing.

TABLE 3 The eligibility (inclusion and exclusion) criteria for the participants in the feasibility study (Study I), the systematic review (Study II), and the dual-center randomized controlled trial (Study III).

Eligibility criteria	Study I	Study II	Study III
Age			
60-75 years	x		x
60 years and older with no upper age limit		x	
Live in the region of Jyväskylä, Finland	x		x
Live in the region of Turku, Finland			x
First primary, unilateral TKR	x		x
Knee osteoarthritis (M17.0, M17.1)	x		x
Mechanical axis of the limb in varus	x		x
Posterior stabilizing or cruciate-retaining prosthesis			x
No fractures, rheumatoid arthritis, or other biomechanical disruptions in the affected lower limb within one year before surgery	x		x
No diagnosed memory disorder	x		x
No neurological condition		x	x

TKR = total knee replacement
M17.0 = Bilateral primary osteoarthritis of knee, M17.1 = Unilateral primary osteoarthritis of knee

4.3 Exercise and Exergaming

4.3.1 Feasibility of exergames

In the feasibility study (Study I), each participant participated in a single, individually organized test session with no other participant present. The participant performed standard post-TKR exercises (n=10) and exergames (n=10) that were developed by Turku GameLab (Futuristic Interactive Technologies research group, Turku University of Applied Sciences, Finland) based on standard post-TKR exercises. This meant that the participants played exergames using similar movements compared to that of standard post-TKR exercises.

The standard exercises and exergames were performed sequentially; first, the standard exercises and second, the exergames immediately after the standard exercises. The standard exercises were ankle pumping while in the supine position, first knee extension while in the supine position, knee flexion while in the supine position, second knee extension while in the supine position, third knee extension while in the supine position, knee flexion while in the sitting position, knee extension while in the sitting position, first knee extension while standing, second knee extension while standing, and knee flexion while standing (FIGURE 3A). The participants performed 10 repetitions in each standard exercise at their preferred pace, except 20 repetitions in the ankle pumping exercise in fast pace. Exergames were the Rowing game, Cave Game, and Intruders (i.e., knee extension-flexion games), the Squat Pong and Pick Up (i.e., squatting games), the Bubble Runner and Hat Trick (i.e., weight shifting games), and the Brick Breaker, Toy Golf, and Hiking (i.e., piloting games) (FIGURE 3B). The Cave game and Intruders were played in a sitting position, while the other games were played while standing. The total duration of one game averaged one and half minutes.

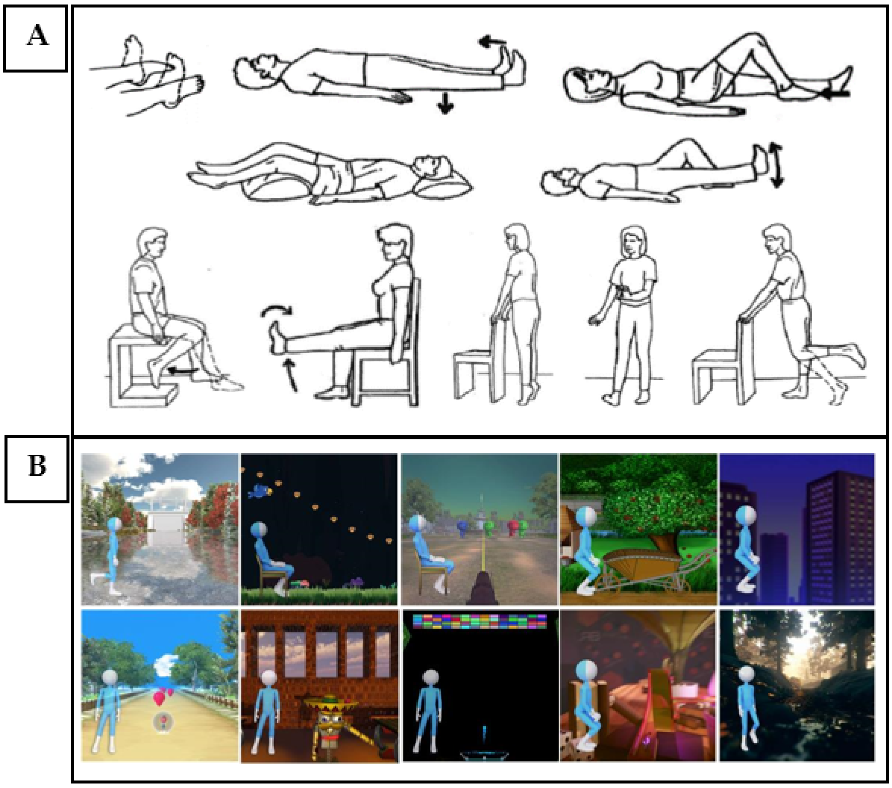

FIGURE 3 Standard exercises (A) and exergames (B) employed in the feasibility study (Study I).

The researcher launched the games from a laptop computer (Micro-Star International, Taiwan) on which the games were installed. The laptop was connected to a Kinect 2 motion sensor (Microsoft, USA) and a flat-screen TV, the latter using a High-Definition Multimedia Interface cable. While playing, the movements of the participant tracked by the Kinect sensor were shown on the television screen as the avatar's movements, i.e., the participant followed the storyline of the game, which guided the participant on the movement that should be performed next. The participants were asked to play the games for their entire duration or until the repetition maximum defined for the game was performed. The description of performance of the standard exercises and exergames are presented in more detail in the original publication (Study I).

4.3.2 Effects of exergaming on physical function and pain

In the systematic review (Study II), in the intervention group, exergaming was characterized as an exercise that had game elements and required bodily movements. In the control group, the participants either had no exercise (i.e., inactive control) or other type of exercise (i.e., active control). In the inactive control group, the participants for example continued their daily living. In the active control group, the participants could have exercise protocol like resistance and balance training or training with cognitive tasks, or they could have different types of exergaming. There was no restriction in the duration of interventions.

In the dual-center RCT (Study III), for four months after discharge from hospital, the participants in the intervention group followed the home-based post-TKR exergame protocol. The exergame protocol included the exergames studied in the feasibility study (Study I) and updated for this dual-center RCT. The overall operation, feedback given to the player and the accuracy of motion detection in exergames were improved, and intensities (slow/moderate/fast) were added to three games (the Intruders, Rowing Game, and Hat Trick). In addition, a new knee stretching game, the Cannon, which was played while sitting, was added to the protocol. Moreover, new software programs were taken into use.

The content of 4-months (16-weeks) exergame protocol (FIGURE 4) was built for the participants using Physiotools Online exercise library software (Physiotools, Tampere, Finland), which the participants used with the training software (GoodLife Kiosk Trainer, GoodLife Technology, Kotka, Finland) installed on a tablet (Lenovo, China). New video instructions on the movements to be performed in the exergames were added and those were visible to the participants on the tablet computer throughout the intervention period. The exergames of the current week of the intervention period were only visible for that week as one session. This meant that when the participant started for example, the exergame session assigned for the second week, the Cave Game was shown twice, the Rowing Game once, the Bubble Runner twice, and the Cannon once. After the participant had played the Cave Game once, the next game, i.e., the Cave Game for the second time, was automatically shown to the participant. After the second Cave Game, the next game, i.e., the Rowing Game, was shown next and so on. In other words, the participant performed exergames of the week in one exergaming session on the sequence shown in FIGURE 4. The instructions for the participants in the intervention group were that they would play the games assigned for the intervention week in question several times a day. In addition, from week 5 to week 12, the exergames that were not planned for the current week but had been in the exergame protocol in the previous weeks were available as additional exergames of the week. For example, the Rowing Game in the week 5.

The exergame protocol in the intervention group was initiated on the third post-operative day. To ensure the progression of the exergaming for 4 months, the number and duration of games, the number of repetitions and series, and the intensity of the games were increased weekly. During the last four weeks, exergames of the most demanding level were performed, i.e., the exergames that had the most repetitions and sets and the fastest versions of them were used.

The participants in the control group followed post-TKR home-exercises by the standard protocol initiated on the first post-operative day. The number and content of exercises in the standard exercise protocol depended on the hospital in which the participant underwent TKR surgery; either Turku University Hospital (Turku University Hospital, 2021) or Central Finland Central Hospital, currently Central Finland Hospital Nova (Hospital Nova, 2020). Although there were small differences in the post-TKR exercises between hospitals, they similarly meet the post-TKR rehabilitation requirements. The upward trend of standard protocol exercising was ensured by increasing the exercise times, and number of repetitions, and sets. The participants in the control group were instructed to complete the exercise protocol several times a day. The participants in the intervention group were similarly instructed to start standard exercising on the first post-operative day and to follow it on days when they could not exergame (for example, days when they were away from their residence). The interventions are presented in a more detailed manner in the original publication (Study III).

	KNEE EXTENSIO-FLEXION				KNEE FLEXION / SQUAT				WEIGHT SHIFTING			STRETCHING		FUNCTIONAL	
Week	**Game 1**	**ROM**	**Reps/Time**	**Sets**	**Game 2**	**ROM**	**Reps/Time**	**Sets**	**Game 3**	**Time**	**Sets**	**Game 4**	**Time**	**Game 5**	**Time**
1	CaveGame	110°-0°	5	2	RowingGame (S)	110°-0°	15 / 120s	1	Bubblerunner	90s	1	Cannon	120 s		
2	CaveGame	110°-0°	7	2	RowingGame (M)	110°-0°	17 / 120s	1	Bubblerunner	120s	2	Cannon	120 s		
3	CaveGame	110°-0°	10	2	RowingGame (M)	110°-0°	17 / 120s	1	Bubblerunner	120s	2	Cannon	120 s		
4	CaveGame	110°-0°	10	3	RowingGame (F)	110°-0°	25 / 120s	1	HatTrick (S)	120s	2	Cannon	120 s		
5	CaveGame	110°-0°	12	3	PickUp		120s	2	HatTrick (M)	150s	2	Cannon	120 s		
6	Intruders (S)	110°-0°	10 / 120s	2	PickUp		150s	2	HatTrick (M)	180s	2	Cannon	120 s		
7	Intruders (M)	110°-0°	10 / 120s	2	PickUp		180s	2	HatTrick (F)	180s	2	Cannon	120 s	Hiking	180 s
8	Intruders (M)	110°-0°	10 / 120s	3	PickUp		180s	2	BrickBreaker	120s	2	Cannon	120 s	Hiking	240 s
9	Intruders (F)	110°-0°	10 / 120s	3	SquatPong (S)		60s	2	BrickBreaker	120s	2	Cannon	120 s	ToyGolf	360 s
10	CaveGame	110°-0°	12	3	SquatPong (M)		90s	2	BrickBreaker	180s	2	Cannon	120 s	ToyGolf	360 s
11	CaveGame	110°-0°	12	3	SquatPong (M)		120s	2	BrickBreaker	180s	2	Cannon	120 s	ToyGolf	360 s
12	CaveGame	110°-0°	12	3	SquatPong (F)		180s	2	HatTrick (F)	180s	2	Cannon	120 s	ToyGolf	360 s
13-16	Player choose at least one: CaveGame or Intruders (F)				Player choose at least one: RowingGame (F) or SquatPong (F) or PickUp				Player choose at least one: Bubblerunner or HatTrick (F) or BrickBreaker			Cannon	120 s	Free play: Hiking and/or ToyGolf	
(S) = Slow pace, (M) = Moderate pace, (F) = Fast pace, ROM = range of motion															

FIGURE 4 The progressive 4-months exergame protocol in the dual-center randomized controlled trial (Study III).

4.4 Measurements and data collection

The summary of the data collected in this thesis are presented in TABLE 4.

TABLE 4 Summary of the measurements collected in the feasibility study (Study I), the systematic review (Study II), and the dual-center randomized controlled trial (Study III).

	Study I	Study II	Study III
Demographics			
Age	x	x	x
Sex	x	x	x
Feasibility			
Movement characteristics	x		
Perceived exertion and knee pain	x		
Physical function and pain			
Walking		x	x
Mobility			x
Knee-related symptoms and physical function	x		x
Knee joint range of motion	x		x
Lower extremity performance			x
Muscle strength			x
Others			
Satisfaction with the operated knee			x
Adherence			x
Adverse events			x
Physical activity			x

4.4.1 Feasibility

4.4.1.1 Movement characteristics

In the feasibility study (Study I), the volume (as duration and repetitions), range (as knee joint ROM), and intensity (as angular velocity and angle accumulation) of movement were determined while the participants performed knee extension-flexion movements while exergaming and standard post-TKR exercising. To specify the movement characteristics, video recording throughout standard exercises and exergames was used with the participant standing sideways with the operated lower limb toward the video camera (Sony RX-10 III, Sony Corporation, Japan). Of the standard exercises, three were video recorded: knee flexion and extension exercises while sitting (the Flexion Sitting and Extension Sitting) and knee flexion exercise while standing (the Flexion Standing). The performance of all exergames were video recorded. However, the movement characteristics were not analyzed from piloting exergames (the Brick Breaker, Toy Golf, and Hiking), which were performed for future development purposes.

A sagittal two-dimensional model was created using Vicon Motus motion analysis software version 10.01.1 (Vicon Motion Systems Ltd, Oxford, UK) after videos were converted to the AVI format using Kinovea software version 0.8.15 (Kinovea, Le Taillan-Médoc, France). In addition, force plate measuring was used to specify the intensity of movement throughout the performance of two weight shifting exergames, i.e., the amount of weight (produced resultant force) the participants moved to the operated lower limb during the movement. A force measure was captured using Vicon Nexus 2 software (Vicon Motion Systems Ltd, Oxford, UK) while the participant stood on AMTI MiniAMP MSA-6 force plates (Advanced Mechanical Technology Inc., Phoenix, Arizona, AZ, USA).

4.4.1.2 Perceived exertion and knee pain

In the feasibility study (Study I), the perceived exertion and knee pain during the standard post-TKR exercises, and during the knee extension-flexion, squatting, and weight shifting exergames were rated using the Borg Rating of Perceived Exertion (RPE) (Borg, 1982) and the pen-and-paper visual analog scale (VAS) (Thong et al., 2018), respectively (Study I). The scoring of physical exertion in the RPE is from 6 to 7 (Very, very light), 8 to 10 (Very light), 11 to 12 (Fairly light), 13 to 14 (Somewhat hard), 14 to 15 (Hard), 16 to 17 (Very hard), and 18 to 20 (Very, very hard). The rating in VAS is from 0 (no pain) to 100 (worst possible pain); 0 to 4 (no pain), 5 to 44 (mild pain), 45 to 74 (moderate pain), and 75 to 100 (severe pain) (Jensen et al., 2003).

4.4.2 Physical function and pain

4.4.2.1 Mobility and walking

In the dual-center RCT (Study III), the mobility was assessed using the TUG test. In the systematic review (Study II), the TUG test was used to assess walking. In addition, walking was assessed with the walking speed tests (Rydwik et al., 2012) (Studies II & III), such as 10-meter walking test (10-MWT) (Unver et al., 2017), the 2- or 6-minute walking test (W. L. S. Chan & Pin, 2019) (Study II), the Functional Gait Assessment (Wrisley & Kumar, 2010) (Study II), the Dynamic Gait Index (Study II), and the Tinetti's Gait (Parveen & Noohu, 2017) (Study II). In the TUG test, the time is recorded while a person gets up from a chair, walks three meters, and returns to sit down. In the walking speed test, the time is recorded using a stopwatch or photocells while a person walks the distance specified for the test, such as 10 meters, at a habitual or fast pace. In the 2- or 6-minute walking test, the distance is recorded while a person walks the time specified for the test. The Functional Gait Assessment, Dynamic Gait Index, and Tinetti's Gait are tests that include 10, 8, and 7 tasks, respectively, assessing walking. The tasks are scored from 0 to a maximum of 3, from poor to normal walking performance. In the above tests, a faster time, a higher value of meters per second, a longer distance, or higher score indicates better mobility or walking performance.

4.4.2.2 Knee-related symptoms and physical function

The knee-related symptoms and physical function after TKR was assessed using the WOMAC in the feasibility study (Study I) and the OKS questionnaire in the dual-center RCT (Study III). The WOMAC questionnaire included 24 items that the participants scored from 0 to 4, from the lowest to the highest severity of knee pain (5 items, score 0–20), knee stiffness (2 items, score 0–8), and knee-related physical function (17 items, score 0–68). The total score ranges from 0 to 96, with 0 indicating the least (or no) knee pain and knee stiffness, and the best knee-related physical function in the past 48 hours. The OKS questionnaire included 12 items that the participants scored from 0 (highest severity of function and pain) to 4 (lowest severity of function and pain). The maximum total score of 48 indicated the best knee-related physical function and the least knee pain in the past four weeks. Grading for the OKS total score is "Poor" (0 to 19), "Moderate" (20-29), "Good" (30 to 39) and "Excellent" (40 to 48).

In addition, in the feasibility study (Study I) and in the dual-center RCT (Study III), the knee pain of the participants was assessed separately using a pen-and-paper VAS. The participants rated their average knee pain that had occurred during the past 24 hours (Study I) and over seven days (Study III) prior to the day of assessment visit.

4.4.2.3 Knee joint range of motion

In the feasibility study (Study I) and in the dual-center RCT (Study III), the current knee joint ROM was determined from the operated lower limb using the goniometer (Gogia et al., 1987). The active knee joint ROM in degrees was measured while the participant was in a supine position. A smaller degree in the knee extension and a larger degree in the knee flexion indicated better knee joint ROM.

4.4.2.4 Lower extremity performance

In the dual-center RCT (Study III), the lower extremity performance was determined using the short physical performance battery (SPPB) test (Guralnik et al., 1994). Each of the three sub-tests of the SPPB test (balance, mobility, lower extremity strength) were scored from 0 (poor performance) to 4 (best performance). The SPPB total score ranged from 0 to 12, with a higher score indicating better lower extremity performance.

4.4.2.5 Muscle strength

In the dual-center RCT (Study III), the muscle strength was determined from the operated lower limb with isometric knee extension and flexion force test using the Metitur Good Strength dynamometer (Newtons [N]) and the Con-Trex Multijoint dynamometer (Newton-meters [Nm]). The data were standardized to Newton-meters by calculating Newtons into Newton-meters using the formula {Force (Newton) * lever arm length of the leg (meter)}. The results were expressed in Newton-meters (Nm) normalized on body weight (kg). A higher Nm/kg value in the force test indicated better muscle strength.

4.4.3 Others

4.4.3.1 Satisfaction with the operated knee

In the dual-center RCT (Study III), the participants rated their early satisfaction with the operated knee by answering the question: "How satisfied are you with your operated knee?". This question was asked at the end of 4-month intervention, and the response options ranged from 1 ("Very satisfied") to 4 ("Very dissatisfied").

4.4.3.2 Adherence

In the dual-center RCT (Study III), the adherence data on standard exercising and exergaming were gathered using structured diaries. The participants began reporting on the daily standard exercising (intervention and control group) and exergaming (intervention group) from the first postoperative day and continued it for 4 months to the end of the intervention. The diary entries for one day were: 1) information on whether the standard exercising and/or exergaming was done (Yes/No), 2) the number of times standard exercising and/or exergaming were performed, and 3) the total duration of the standard exercising and/or exergaming in minutes.

In addition, in the dual-center RCT (Study III), the gaming computers recorded the duration (seconds) of exergames played by the participants in the intervention group daily.

4.4.3.3 Adverse events

In the dual-center RCT (Study III), the adverse events that the study participants spontaneously reported were recorded. The causal relationship with the intervention and possible drop-outs caused by them were assessed and recorded. Moreover, in the case of drop-out, it was assessed whether it was due to the state of health or personal will of the participant, or whether the participant was not reached.

4.4.3.4 Physical activity

In the dual-center RCT (Study III), the participants reported daily physical activity (PA) for four months using structured diaries. The diary entries for one day were: 1) codes of PA, 2) the total durations per PA code in minutes, and 3) the intensity (light, moderate, and vigorous) per PA code. The code of PA depended on whether PA was leisure time, daily errands or commuting, and the specific activity (e.g., swimming, renovation, or bicycling to work). The results were expressed as weekly metabolic equivalent of task hours (METh) based on weekly mean minutes and reported activity and intensity (Ainsworth et al., 2011).

4.5 Data processing for analysis

4.5.1 Movement characteristics

In the feasibility study (Study I), data processing for analysis was carried out for movement characteristics. A custom MATLAB script (MathWorks, USA) was used to identify the movement characteristics performed during standard post-TKR exercising and exergaming: 1) the volume of movement was determined from the duration of performed exergames or standard post-TKR exercises and from repetitions performed during extension-flexion and squatting movements in those exergames and exercises, 2) the range of movement was determined from the knee joint ROM during extension-flexion and squatting movements, and 3) the intensity of movement was determined from the angular velocity and angle accumulation during extension-flexion and squatting movements, or by the resultant force during the weight shifting movement. To calculate and compare the movement characteristics performed in the standard exercises and exergames, the cutoff values were defined for each participant individually to determine the active movement and the repetitions and knee ROM during it. Moreover, the target area of the repetitions was determined from the active knee ROM measured by the goniometer. Data processing of movement characteristics has been presented in more detail in the original publication (Study I).

4.5.2 Data extraction and quality assessment

In the systematic review (Study II), the references of the studies identified in the database and manual searches were imported to the screening and data extraction tool (Veritas Health Innovation, 2022) for the removal of duplicates, for the two-phase study selection in accordance with the eligibility criteria, and for data extraction. After the removal of duplicates, at the first phase of the study selection, the titles and abstracts were screened to exclude non-relevant studies. At the second phase of the study selection, full texts for the remaining studies were retrieved and screened. At this phase, the reasons for exclusions were reported. All eligible RCTs were carried forward to data extraction and quality assessment, which was performed at the outcome level using the Cochrane Risk of Bias 2 tool (Sterne et al., 2019). The data extraction was performed following a customized format that followed the PICO strategy (Patients, Intervention, Comparison group, Outcomes), and the priority list that defined the order of outcome measures in data synthesis (see the original publication (Study II; Supplementary material A)). The original investigators of published RCTs were contacted if the full text was not available or there were ambiguities in the publication that prevented data extraction and the completion of quality assessment (see the original publication (Study II; Supplementary material A)). All stages of the review process, i.e., eligibility screening, data extraction, and quality assessment of the RCTs were performed as an independent work by pairs of reviewers. Complete agreement between reviewer-pairs was required. If needed, disagreements between reviewer-pairs were solved by a third reviewer. The certainty of evidence in the meta-analysis was rated using the Grading of Recommendations, Assessment, Development, and Evaluation (Schünemann et al., 2013).

4.5.3 Missing data

There were missing data in the exercise and PA diaries and in the muscle strength data in the dual-center RCT (Study III). The missing durations on diaries were imputed using mean imputation. For each week of the diary, an average duration in one day per activity was calculated from the fully reported entries for that week. When the activity had missing durations for some days of the week, the mean duration of the activity calculated for the week was imputed for these days (n=58). When the reported activity was observed to have missing durations for all days of the week, the mean calculated for the same activity on the previous (n=30) or following (n=5) week were imputed. If the participant had not reported the activity on previous or following weeks, the one day mean of the same randomization group was calculated and used (n=23). When the participant had not reported the level of perceived exertion at the activity entries in leisure time or daily errands, the activity was recorded at a moderate level (n=202). However, if participant had reported same activity on previous or following week(s) mainly at the light or vigorous level of exertion, the activity was recorded according to those levels (n=19). Some diary entries in the leisure time or daily errands (n=8) could not be allocated to any activity because the entries were unclear or too incomplete. The muscle strength data was corrected for two participants by calculating the mean leg length in the operated lower limb in cases where the length was not measured at baseline (n=1) and at 4-month follow-up (n=1). This calculated leg length was used in the analysis of force measurement for these two participants. Otherwise, the missing data resulting from interferences and interruptions to routine data collection were not imputed. In addition, the exergaming data from one gaming computer was lost and left out from analysis, i.e., the data were not imputed.

4.6 Sample sizes

The intended sample sizes were 20 for the feasibility study (Study I) and 100 for the dual-center RCT (Study III). The sample size calculation for the Study III was based on the primary outcome OKS and was determined to detect a 5-point difference between the intervention and control groups (at an alpha of 0.05 and power of 80%), and to anticipate a 10% drop-out rate in groups during the follow-up (Beard et al., 2015; Judge et al., 2012).

4.7 Statistical methods

In the feasibility study (Study I), the movement characteristics (the volume, range and intensity) are presented in the median and interquartile range or mean and SD. Analyses of the differences in the movement characteristics (the range and intensity) between standard exercises and exergames were performed with the Wilcoxon signed rank test with the level of significance set at 0.05.

In the systematic review (Study II), a random effects model and restricted maximum-likelihood estimation were used to assess the treatment effect in the meta-analysis (R Core Team, 2019; Viechtbauer, 2010). The effect sizes between groups were reported as the standard mean difference (SMD, Hedges' g) with 95% confidence intervals (CI), and were interpreted small (g=0.2), medium (g=0.5), or large (g=0.8) (Cohen, 1988). In the meta-regression analysis, the included covariates together with high risk of bias were the participants' mean age and baseline walking performance, exercise traits, such as the duration of intervention and number of sessions per week, type of comparison group, and technology used. For studies that did not measure the covariates included in the meta-regression, multiple imputation with a log-linear model was applied to include them in the analysis (van Buuren, 2018; van Buuren & Groothuis-Oudshoorn, 2011). In addition, statistical heterogeneity was explored with statistics (Q, I-squared), and evaluated from the forest and funnel plots. Moreover, a selective publication bias was evaluated from the funnel plot (Sterne et al., 2011).

In the dual-center RCT (Study III), the intention-to-treat (ITT) principle was used in analyses of physical function and pain, i.e., the participants were included in the ITT analysis if they received the allocated intervention in the intervention or control groups and had assessments at the baseline and 2- or 4-month follow-up. The changes in the primary and secondary outcomes between the intervention and control groups were analyzed using mixed-effects models and an unstructured covariance structure, including group, time, and group*time interactions (Kenward & Roger, 1997). The results are presented as mean and 95% CI. The level of significance was set at 0.05 for statistical analyses. Moreover, the adherence on exergaming and standard exercising and the level of PA are presented in mean and 95% CI.

The statistical software used in the analyses were IBM SPSS Statistics (IBM Corporation, USA), R (version 4.0.3) (R Core Team, 2020) (Studies I, II, & III) and Stata (version 17.0; StataCorp LLC, USA) (Study III).

5 RESULTS

5.1 Characteristics of the participants (Studies I, II, & III)

In this systematic review (Study II), total of 3797 participants representing a mixed population of older adults without neurologic condition were included. The samples in the feasibility study (Study I) and in the dual-center RCT (Study III) consisted of 7 and 52 older adults with TKR, respectively. In all studies (I-III), the mean age varied between 65 and 74 years, and the majority of the participants were women. The baseline characteristics of the participants are presented in a more detailed manner in TABLE 5.

TABLE 5 Baseline characteristics of the participants in the feasibility study (Study I), the systematic review (Study II), and the dual-center randomized controlled trial (Study III).

	Study I	Study II		Study III	
		Intervention group	Control group	Intervention group	Control group
	n=7	n=1822	n=1975	n=25	n=27
Age, years, mean (SD)	65.6 (4.8)	74.3 (6.0)	74.3 (5.8)	66.9 (3.1)	66.4 (4.5)
Women, %	85.7	61.7	60.6	64.0	63.0
Physical function, mean (95% CI)					
OKS, score (0-48)				26.6 (24.0-29.3)*	27.0 (24.5-29.4)
TUG, s				9.5 (8.1-10.9)	8.2 (7.5-8.9)
10-MWT, fast pace, m/s				1.6 (1.4-1.7)	1.6 (1.5-1.7)
SPPB; total, score (0-12)				9.6 (8.9-10.2)	9.8 (9.2-10.4)
SPPB; balance, score (0-4)				3.8 (3.6-4.0)	3.8 (3.6-4.0)
SPPB; mobility, score (0-4)				3.8 (3.5-4.0)	3.9 (3.8-4.0)
SPPB; LE strength, score (0-4)				1.9 (1.5-2.4)	2.1 (1.6-2.5)
Muscle force; extension, Nm/kg				102.5 (83.9-121.0)	94.8 (81.0-108.6)†
Muscle force; flexion, Nm/kg				52.1 (41.1-63.1)	48.0 (39.4-56.6)†
Active ROM; flexion, degree	98.6 (84.0-113.1)			107.8 (100.6-115.0)	105.5 (99.8-111.3)
Active ROM; extension, degree	11.4 (7.6-15.2)			6.8 (3.9-9.8)	7.3 (5.2-9.5)
Pain, mean (95% CI)					
Past 24 hours (0-100)	38 (15.6-60.4)				
Past 7 days (0-100)				54.8 (46.3-63.2)	53.7 (45.4-61.9)
WOMAC, past 48 hours, mean (95% CI)					
Pain (0-20)	5.3 (2.5-8.1)				
Stiffness (0-8)	2.3 (1.1-3.5)				
Physical function (0-68)	19.1 (9.8-43.6)				

* n=24, † n=25

10-MWT = 10-meter walking test, LE = lower extremity, OKS = Oxford Knee Score, ROM = range of motion, SPPB = Short Physical Performance Battery, TUG = Timed Up and Go, WOMAC = Western Ontario and McMaster Universities Osteoarthritis index

5.2 Feasibility of exergames in rehabilitation after total knee replacement (Study I)

The feasibility of exergames was investigated as kinematics during the performance of exergames customized for post-TKR rehabilitation and compared with that of kinematics during the performance of standard post-TKR exercises. Kinematics were analyzed in the feasibility study (Study I) that evaluated movement characteristics and, in addition, strain and pain during single-session standard exercise and exergaming.

5.2.1 Movement characteristics as the volume, range, and intensity of movement

The volume of movement (TABLE 6). The total duration of exercise in exergames (the Cave Game, Intruders, Rowing Game, Squat Pong, and Pick Up) varied approximately between 1 and 3 minutes. In standard exercises (the Extension Sitting, Flexion Sitting, and Flexion Standing), the duration was shorter. The number of repetitions in the exergames was on average two to three times higher than that in the standard exercises. When the number of repetitions was proportional to the duration, i.e., repetitions/minute, it was lowest in the Cave Game and highest in the Rowing Game while it was more similar in other exergames and in the standard exercises. During the performance of the Intruders, Extension Sitting, and Flexion Sitting, the repetitions were closest to the goniometer that measured active knee ROM. During the performance of Squat Pong, no repetitions reached the goniometer that measured flexion and in the Pick Up the percentage remained low.

The range of movement (TABLE 7). In exergames and standard exercise with knee extension as primary movement, a significant difference in the degree of knee joint ROM was seen in the Cave Game compared with the Extension Sitting. The participants extended the operated knee significantly lesser in the exergame than in the standard exercise. When the Rowing Game was compared with the Flexion Standing, significantly higher knee flexion was seen in the exergame. The participants had significantly higher knee flexion in the standard exercises with knee flexion as primary movement compared with squatting exergames, the Squat Pong, and Pick Up.

The intensity of movement (TABLE 7). In post-TKR exergames with knee extension as the primary movement, the angular velocity in the Intruders was significantly more intense than in the Extension Sitting exercise. In the exergames with the knee flexion as primary movement, the Rowing Game was significantly more intense compared with the Flexion Sitting exercise. In addition, the Squat Pong exergame was more intense than the Flexion Standing exercise.

In the weight shifting exergames, the Bubble Runner and Hat Trick, visual inspection of FIGURE 5 suggest that the participants produced less resultant force with the operated lower limb.

TABLE 6 The volume of movement in the exergames and standard exercises after total knee replacement by the primary movement: A) knee extension, and B) knee flexion.

A

	n	Duration [s]	Repetitions		
			[Total no]	[reps/min]	[% in active ROM]
		med (IQR)	med (IQR)	med (IQR)	mean (SD)
Cave Game*	7	177 (21)	24 (10)	8 (2)	80 (14)
Intruders*	6	70 (85)	19 (7)	15 (8)	96 (3)
Extension Sitting‡	7	36 (15)	10 (1)	15 (6)	100 (0)

B

	n	Duration [s]	Repetitions		
			[Total no]	[reps/min]	[% in active ROM]
		med (IQR)	med (IQR)	med (IQR)	mean (SD)
Rowing Game*	7	62 (8)	31 (14)	34 (11)	83 (37)
Squat Pong†	7	118 (32)	28 (8)	14 (3)	0 (0)
Pick Up†	6	93 (4)	21 (3)	14 (1)	14 (33)
Flexion Sitting‡	7	42 (20)	9 (3)	13 (5)	97 (8)
Flexion Standing‡	7	40 (7)	10 (0)	15 (3)	61 (44)

*Knee extension-flexion exergames
†Squatting exergames
‡Standard exercises
ROM = range of motion, med = median, IQR = interquartile range

TABLE 7 The range and intensity of movement in the exergames and standard exercises after total knee replacement and significance levels for the differences between exergames and between exergames and standard exercises by the primary movement: A) knee extension and B) knee flexion.

A

	n	Knee joint ROM [°] med (IQR)	Angular velocity [°/s] mean (SD)	Angle accumulation [°/min] mean (SD)	Cave Game Range *P*-value	Cave Game Intensity *P*-value	Intruders Range *P*-value	Intruders Intensity *P*-value
Cave Game*	7	14 (5)	25.1 (11.0)	1297.8 (469.4)				
Intruders*	6	11 (5)	74.4 (36.6)	2769.7 (2094.5)				
Extension Sitting‡	7	11 (5)	35.5 (20.4)	1973.2 (878.7)	0.018	0.176	0.345	0.046

B

	n	Knee joint ROM [°] med (IQR)	Angular velocity [°/s] mean (SD)	Angle accumulation [°/min] mean (SD)	Rowing Game Range *P*-value	Rowing Game Intensity *P*-value	Squat Pong Range *P*-value	Squat Pong Intensity *P*-value	Pick Up Range *P*-value	Pick Up Intensity *P*-value
Rowing Game*	7	93 (11)	67.6 (29.8)	5021.2 (1976.8)						
Squat Pong†	7	56 (14)	20.1 (9.7)	1249.5 (606.7)						
Pick Up†	6	70 (14)	28.1 (8.9)	1666.6 (560.5)						
Flexion Sitting‡	7	94 (13)	20.9 (6.6)	1071.3 (403.2)	0.237	0.018	0.018	0.735	0.028	0.173
Flexion Standing‡	7	89 (14)	36.9 (9.6)	2083.0 (441.7)	0.018	0.063	0.018	0.018	0.046	0.046

*Knee extension-flexion exergames

†Squatting exergames

‡Standard exercises

ROM = range of motion, med = median, IQR = interquartile range, SD = standard deviation

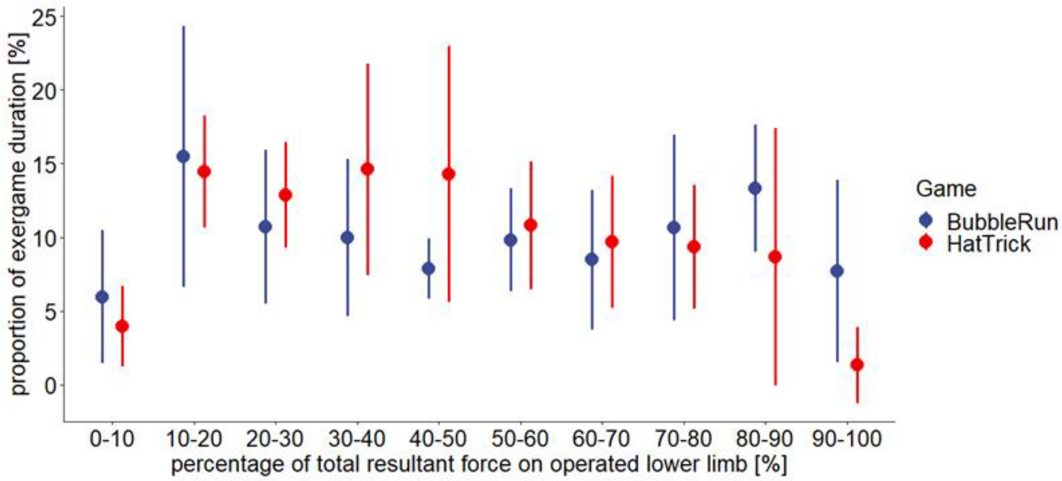

FIGURE 5 The resultant force (the mean and SD) produced by the participants (n=7) with the operated lower limb during the weight shifting exergames.

5.2.2 Perceived exertion and knee pain

Older adults with TKR who had had a maximum duration of four months since the surgery (n=7), considered their physical exertion to be "Fairly light" (median, 12 (IQR, 5)) and knee pain to be mild (8 (6)) after performing standard post-TKR exercises. After performing knee extension-flexion exergames, the physical exertion was considered as “Fairly light” (11 (3)), and the knee pain was mild (15 (12)). In squatting exergames, the physical exertion was “Somewhat hard” (13 (4)); however, knee pain was mild (7 (17)), and in weight shifting and piloting exergames, the physical exertion was “Very light” (10 (4)), and no pain was experienced (4 (4)).

5.3 Adherence and adverse events in rehabilitation after total knee replacement (Study III)

The adherence and adverse events related to undertaking of home-based training in assigned groups during the 4-month intervention period implemented after TKR surgery were assessed in the dual-center RCT (Study III).

No between-group differences in the total hours of self-reported post-TKR exercising were observed, i.e., exergaming and standard exercise in the intervention group and standard exercise in the control group. The participants in the intervention group (n=21) reported a mean of 25.6 hours (95% CI: 14.9 to 36.4) of exergaming and standard exercise during weeks 1 to 8, and 20.2 hours (11.6 to 28.7) during weeks 9-16. The participants in the control group (n=25) reported 19.0 hours (12.0 to 26.0) of standard exercise during weeks 1 to 8, and 17.4 hours (8.8 to 26.1) during weeks 9 to 16. Similarly, there was no change in exergaming in the intervention group (n=20) when assessing the total minutes exergamed from the computer data. The mean number of minutes were 508.3 (213.0 to 803.6) during weeks 1 to 8, and 333.7 (129.5 to 537.8) during weeks 9-16. Two participants in the intervention group did not exergame, and some participants exergamed during the intervention period for less than 2 (n=3), 3 (n=2), or 4 (n=3) months. The percentage of days of the training, i.e., exergaming and standard exercising, collected by computers and diaries during the 4-month intervention period are presented in TABLE 8.

TABLE 8 Percentages of exergaming and standard exercising days collected using computers and diaries during the 4-month intervention period after total knee replacement.

	Intervention group			Control group
	Exergaming		Standard exercising	Standard exercising
Weeks	Computer (%)	Diary (%)	Diary (%)	Diary (%)
1 – 8	40.9 (26.2-55.6)	42.3 (27.9-56.8)	31.4 (17.9-44.9)	64.5 (48.5-80.6)
9 – 16	27.5 (13.1-42.0)	32.0 (17.8-46.2)	18.1 (8.4-27.9)	59.1 (43.8-74.5)
Total	34.2 (20.1-48.4)	37.2 (23.5-50.9)	24.8 (14.4-35.2)	61.8 (48.0-75.6)

The values are mean percentage of days and 95% confidence interval.

In the intervention group and the control group, there were no adverse events related to home-based exergaming or standard exercising.

5.4 Effect of exergaming on the physical function and pain in older adults (Studies II & III)

The effects of exergaming on the physical function and pain in older adults were analyzed with a meta-analysis and meta-regression analysis in the systematic review (Study II) and with the ITT analysis in the dual-center RCT (Study III). Study II investigated the effect of exergame-based interventions on the physical function in individuals without neurologic condition compared with other exercise (active control) or no exercise (inactive control). Study III investigated the effect of the 4-month customized, exergame-based post-TKR intervention on the physical function and pain compared with standard post-TKR exercise. In addition, in the dual-center RCT, the participants' satisfaction with the operated knee after the intervention period and the PA in leisure time, daily errands, and commuting during the intervention period were investigated.

5.4.1 Walking

In the systematic review (Study II), the exergame group improved walking (SMD: −0.21, 95% CI: −0.36 to −0.06; 3102 participants, 58 studies; moderate-quality evidence) (FIGURE 6) compared with the active and inactive control groups. The meta-analysis revealed a small, statistically significant between-group effect favoring the exergame group. At the follow-up point, there were no statistically significant between-group differences (−0.32, -0.64 to 0.00; 1028 participants, 13 studies; low-quality evidence) (FIGURE 7). In a meta-regression analysis, the type of comparison group, i.e., active or inactive, had small (0.48, 0.20 to 0.77) or medium (0.50, 0.19 to 0.81) associations with the effect of exergaming explaining 18.6% or 14.1% of the variance when evaluated independently or together with other covariates, respectively. The statistical heterogeneity was substantial after the intervention (*P*<.0001, I^2 =76.3%) and after the follow-up (*P*<.0001, I^2 =72.8%).

In the dual-center RCT (Study III), the change in the walking speed (m/s) did not differ (*P*=0.06) between the exergame (change: 0.2 m/s, 95% CI: 0.1 to 0.3, n=21) and the standard exercise group (0.1 m/s, -0.0 to 0.2, n=25) after a 4-month intervention period. The within-group improvement was positive only in the exergame group.

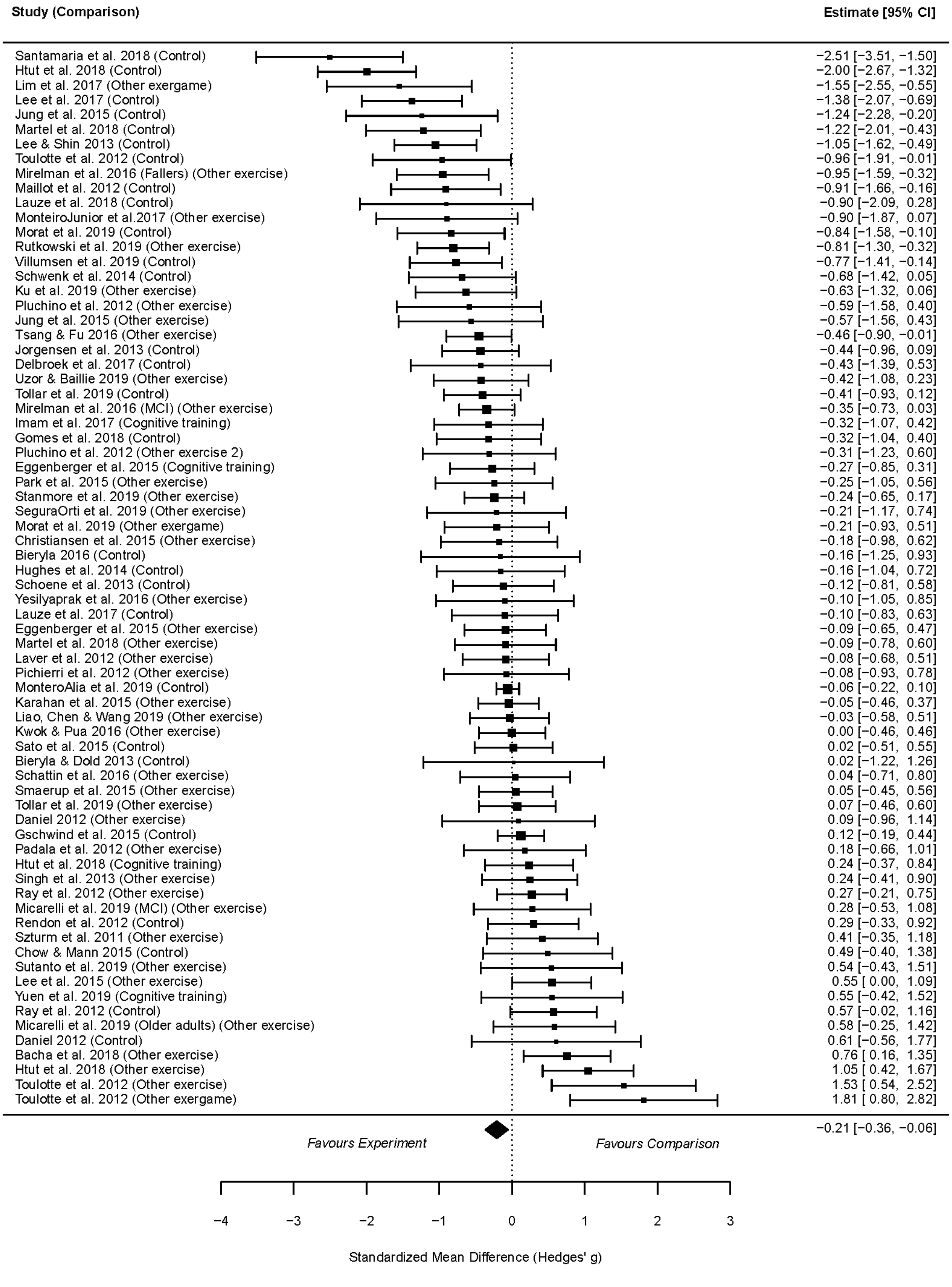

FIGURE 6 The pooled effect sizes of effects of exergaming on walking compared with inactive (Control) and active (Other exergame, Other exercise, Cognitive training) groups after the intervention.

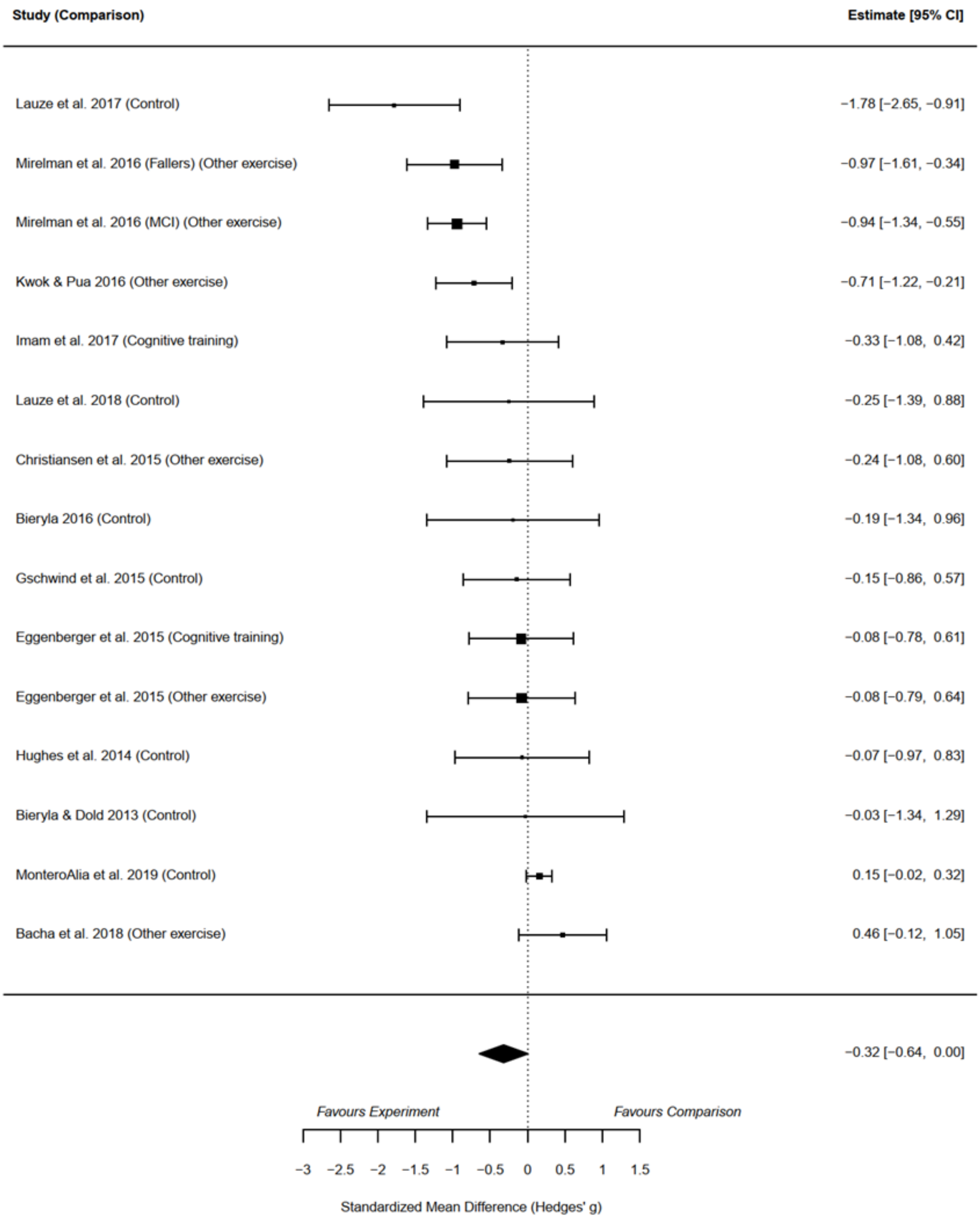

FIGURE 7 The pooled effect sizes of effects of exergaming on walking compared with inactive (Control) and active (Other exergame, Other exercise, Cognitive training) groups after the follow-up.

5.4.2 Mobility

In the dual-center RCT (Study III), the exergame group (n=21) improved the mobility from the baseline at the mid-intervention at the 2-months point (*P*=0.019) and at the end of intervention at 4-months (*P*=0.040) compared with those who had standard post-TKR exercise (n=25) (FIGURE 8).

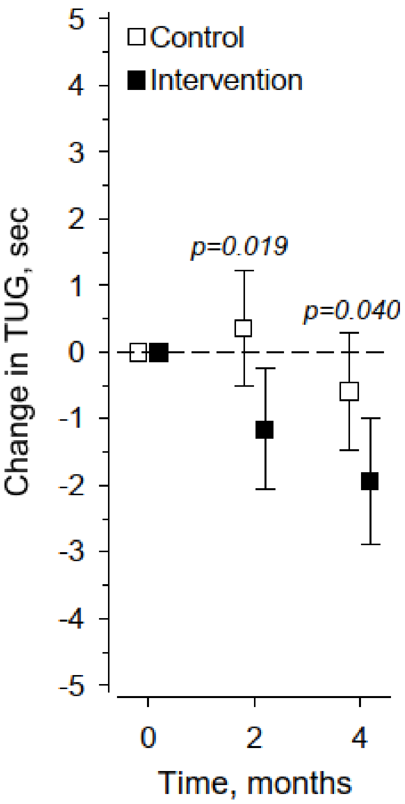

FIGURE 8 Mean changes in mobility measured using the Timed Up and Go in the intervention group (i.e., home-based exergame protocol after total knee replacement, n=21) and in the control group (i.e., home-exercise by standard protocol after total knee replacement, n=25) from the baseline to the mid-intervention at 2-months and to the end of the intervention at 4-months.

5.4.3 Knee-related symptoms and physical function

In the dual-center RCT (Study III), the between group differences in the knee-related pain and physical function (OKS) over the 4-month intervention can be seen in **Error! Reference source not found.**A. The positive within-group mean change in the OKS score after a 4-month intervention was 12.1 (95% CI: 9.1 to 15.1) in the exergame group (n=21) and 9.8 (7.1 to 12.6) in the standard exercise group (n=25). There were no statistically significant between-group differences (*P*=0.27).

The between group differences in knee pain (VAS) over the 4-month intervention in the dual-center RCT (Study III) can be seen in **Error! Reference source not found.**B. The positive within-group mean changes in VAS after a 4-month intervention was -36.3 mm (95% CI: -46.7 to -25.8) in the exergame group (n=21) and -26.7 mm (-36.4 to -17.0) in the standard exercise group (n=25). There were no statistically significant between-group differences (*P*=0.18).

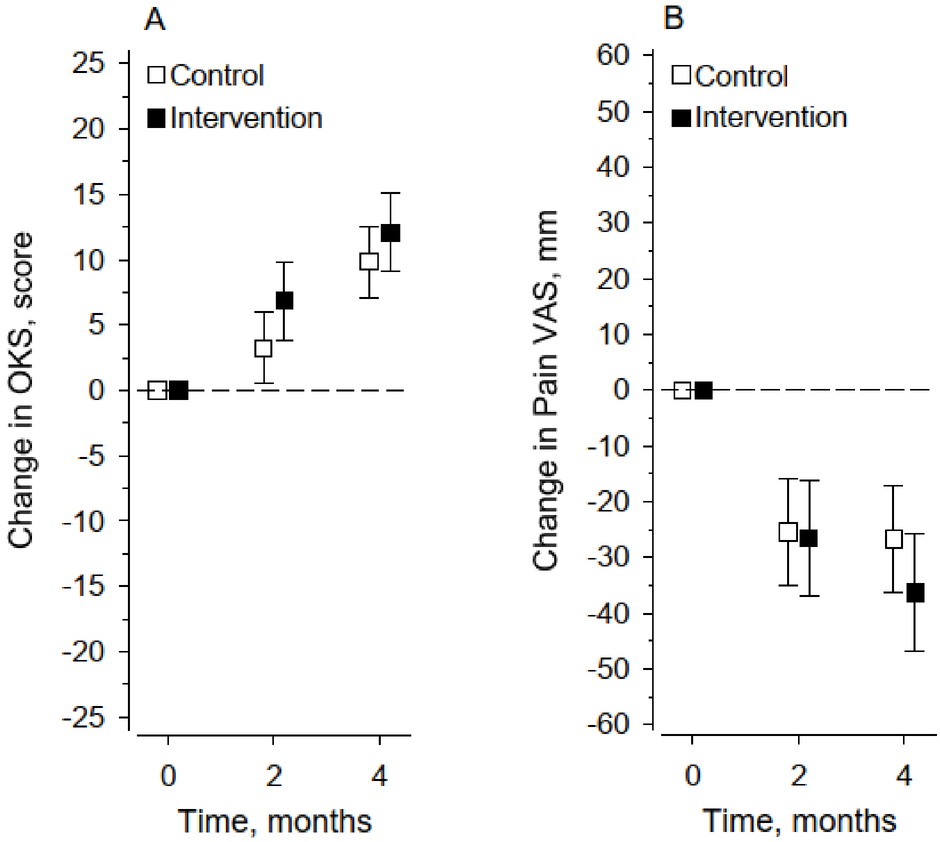

FIGURE 9 Mean changes in knee-related pain and physical function measured using the Oxford Knee Score (A) and knee pain measured using the visual analog scale (B) in the intervention group (i.e., home-based exergame protocol after total knee replacement, n=21) and in the control group (i.e., home-exercise by standard protocol after total knee replacement, n=25) from the baseline to the mid-intervention at 2-months and to the end of intervention at 4-months.

5.4.4 Knee joint range of motion

In the dual-center RCT (Study III), the within-group mean change in knee joint ROM in extension was -0.5° (95% CI: -3.5 to 2.5) in the exergame group (n=21) and 0.1° (-2.7 to 2.9) in the standard exercise group (n=25). The within-group mean change in knee joint ROM in flexion was -1.0° (-8.0 to 5.0) in the exergame group (n=21) and -7.0° (-13.0 to -2.0) in the standard exercise group (n=25). The change in flexion was negative in the standard exercise group. There was no statistically significant between-group change (*P*=0.76 and *P*=0.17).

5.4.5 Lower extremity performance

In the dual-center RCT (Study III), the within-group mean change in the SPPB score was 1.1 (95% CI: 0.4 to 1.7) in the exergame group (n=21) and 0.8 (0.1 to 1.4) in the standard exercise group (n=25). The within-group mean changes in the SPPB subscales, i.e., balance, mobility, and lower extremity strength in the exergame group (n=21) were -0.2 (-0.4 to 0.1), 0.2 (-0.0 to 0.4), and 1.1 (0.6 to 1.6), respectively. In the standard exercise group (n=25), the mean changes were 0.1 (-0.1 to 0.4), 0.1 (-0.1 to 0.3), and 0.5 (0.1 to 1.0), respectively. There were no statistically significant between-group differences in the SPPB scores (P>0.05).

5.4.6 Muscle strength

In the dual-center RCT (Study III), the within-group mean change in the knee extension muscle strength was -0.1 Nm/kg (95% CI: -0.2 to 0.0) in the exergame group (n=21) and -0.1 Nm/kg (-0.2 to 0.0) in the standard exercise group (n=25). The within-group mean change in knee flexion muscle strength was 0.1 Nm/kg (-0.0 to 0.27) in the exergame group (n=21) and 0.1 Nm/kg (-0.0 to 0.1) in the standard exercise group (n=25). There were no statistically significant between-group changes (P=0.85 and P=0.88).

5.4.7 Satisfaction with the operated knee

In the dual-center RCT (Study III), after the intervention period, the exergame group (n=21) was either "Satisfied" (52.4%) or "Very satisfied" (47.6%) with the operated knee. In the standard exercise group (n=23), the participants were "Very unsatisfied" (8.7%), "Unsatisfied" (17.4%), "Satisfied" (39.1%), or "Very satisfied" (34.8%).

5.4.8 Physical activity

In the dual-center RCT (Study III), the participants in the exergame group (n=21) had a higher mean PA during weeks 9 to 16 (179.4 METh (95% CI: 140.7 to 218.1)) than in weeks 1 to 8 (117.5 METh (74.0 to 161.0)). In the control group (n=25), there was no difference in the total PA during weeks 1 to 8 (122.0 METh (54.0 to 190.0)) and weeks 9 to 16 (180.8 METh (120.5 to 241.1)).

6 DISCUSSION

This thesis showed that in older adults, post-TKR exergaming with customized exergames was more effective on mobility compared with standard exercising (Study III). The suitability of these exergames used for post-TKR rehabilitation was verified before the intervention period in individuals who had an average of 10 weeks since the TKR surgery (Study I). Likewise, exergame-based exercising was more effective on walking in older adults without neurological diseases compared with inactive and active comparisons (Study II). Those who exergamed, gained more benefits when compared with those who did not exercise (Study II). In addition, the participants who were assigned to the post-TKR exergame group, adhered similarly to their rehabilitation as the participants in the standard exercise group (Study III). Moreover, they showed more satisfaction with respect to their operated knee and increased their activities in leisure time, daily errands, and commuting alongside the rehabilitation process (Study III).

6.1 Feasibility of exergames in physical rehabilitation

To the best of our knowledge, the movement characteristics and perceived exertion and pain while exergaming and standard exercising have not been previously compared in older adults who have undergone TKR. As expected, in the feasibility study (Study I), most similar movement characteristics were in the range of movement, while more variability was observed in the volume and intensity of movement. The variation was influenced by the longer duration and the faster movement realized in the exergames. Nevertheless, when the performance position and target movements in the exergame were designed to follow more closely to those in standard exercise, the movement volume as assessed through the repetition rate and proportion of repetitions that reached individual knee joint ROM, were most similar.

The biggest and most expected difference, especially with respect to the ROM, was observed between more holistic squatting exergames and standard knee flexion exercises. However, squatting is an effective exercise to increase the weakened lower limb muscle strength and performance, for example, in rising from chair (Yoshiko & Watanabe, 2021). Moreover, squatting targets to strengthen both the operated and unoperated lower limb is important for persons with TKR (Suh et al., 2019). Similarly, the weight shifting and marching exergames included in the post-TKR exergame protocol and performed by the participants in the feasibility study and in the dual-center RCT are useful for increasing the lower body muscle strength (Hai et al., 2022). Furthermore, such exergames may decrease the asymmetry between the operated and non-operated lower limb, which was somewhat visible in the weight transfer games (Study I), and thus also contribute to improvement in the walking performance (Christensen et al., 2021).

Despite or because of the observed but expected differences, it can be observed that our results on the movement characteristics in the knee extension-flexion and weight shifting exergames are a positive indicator of the successful tailoring of games to the rehabilitation needs of TKR patients. Moreover, the perceived exertion during exergaming was light and similar than in standard exercises, except in squat games. However, as mentioned earlier, squatting is a more holistic and intense exercise and therefore, presumably more strenuous. This type of difference has also been observed in an earlier study wherein the participants rated their perceived exertion from low to medium while performing exergames at different difficulty levels (Skjæret-Maroni et al., 2016). Though there was higher perceived exertion after the performance of squat games, the perceived knee pain was mild. Additionally, in weight shifting exergames, the participants had no knee pain during exergaming.

Therefore, our results supported the implementation of these exergames into use in the dual-center RCT. Moreover, an earlier study (Ong et al., 2021) has highlighted that when specific rehabilitation needs of the target group were taken into account in the customization, exergaming produced favorable results on physical outcomes. In summary, it can be stated that before adopting a commercially available or customized exergames as a method of rehabilitation, it would be important to study the movement characteristics to determine if the selected exergames are appropriate for the rehabilitation in question.

6.2 Adherence and adverse events in exergame-based rehabilitation

Research on the adherence on exergaming appears to have some variability and inconsistency in both data gathering and reporting. For example, only 2 of 7 previous studies that explored the effects of exergaming in older adults undergoing TKR and 53.0% of studies in the systematic review (Study II) reported adherence with sufficient information, such as the adherence percentage based on the sessions per day in participants allocated to the exergame group. Also, Bakaa et al. (2021) stated based on their results that approximately half of the studies included in their review did mention adherence; however, only 65% of those reported adherence sufficiently. In addition, Bakaa et al. (2021) reported an objectively measured adherence ranging from 47 to 100% and subjectively measure the adherence ranging from 61 to 110%. In the studies included in the systematic review (Study II), the range was even wider, from 20 to 100%. Variability in exergaming was also seen in the data collected with gaming computers in a dual-center RCT (Study III); 2 participants did not exergame at all, 9 stopped exergaming before the end of the intervention (2 of them stopped in the last week of the intervention period), and 9 participants exergamed until the end of the intervention period (8 of them exergamed every week). It might be possible that these interruptions be related to the TKR surgery, specifically, to the fact that the surgical treatment itself is notable in the improvement of the knee pain and functional ability related to knee OA. Thus, the need and interest in training decreases.

All in all, the most important issue would be to consider the reasons that could affect the adherence to exergaming. In the feasibility study (Study I), for example, the perceived exertion and pain was low during exergaming. The results are based on the low number of participants; however, they are still possible contributors on the enhancement of adherence to exergaming as Collado-Mateo et al. (2021) considered; the absence of discomfort and pain could be related to enjoyment which further contributes to an immediate reward from training and thus, could lead to better adherence. In addition, the absence of adverse events related to exergaming could be a possible contributor to adherence. When rehabilitees do not have, for example, falls while exergaming or delayed muscle pain after exergaming, they may consider exergaming as a safe and comfortable and thus, more engaging exercise method. Moreover, Collado-Mateo et al. (2021) considered technology as one of the key factors for better adherence, when it would offer additional benefits to conduct a physical exercise intervention. However, the variation in the dual-center RCT (Study III) may refer to individuals' preferences; used technology, i.e., exergames might lead to better adherence; however, it may also lead to worse adherence if older adults are unfamiliar or unwilling to use technology.

Further, an increase in the PA during leisure time, daily errands, or commuting may affect exergaming commitment positively or negatively; when other PA increases, the adherence to exergaming remains the same or decrease. However, this could be considered a positive change in both cases, especially for older adults with sedentary behavior (Sašek et al., 2021). It may indicate an increased functional capacity and replacement of therapeutic exercise with other PA. However, in the dual-center RCT (Study III), the adherence to exergaming remained the same toward the end of the intervention in the exergame group, even though activities (PA) in leisure time, daily errands, and commuting increased. It can be hypothesized that exergaming may have even encouraged individuals to perform other PA, for example by reducing the postoperative fear of movement. It can also be hypothesized that by exergaming, rehabilitation progressed more effectively and enabled an increase in other PA. Further studies are needed to increase the knowledge about the reasons that influence the adherence on exergame-based rehabilitation in older adults.

6.3 Effects of exergaming on physical function and pain in exergame-based rehabilitation

6.3.1 Mobility and walking

Mobility and walking are significant variables in terms of independent functioning in older adults. The relevance becomes even more important after a lower extremity surgery, such as TKR, which may have a considerable negative effect on the motor function (Mizner et al., 2005). Therefore, the results of the systematic review (Study II) and the dual-center RCT (Study III) emphasize the effectiveness of exergames in improving walking and mobility in older adults without neurological disorders and more specifically in older adults with TKR. These results also strengthen earlier study results on the effectiveness of exergaming on mobility and walking in older adults (Hai et al., 2022; Hardt et al., 2018; Suleiman-Martos et al., 2022).

In the systematic review for walking (Study II) and in the dual-center RCT (Study III) for mobility, there was a statistically significant change in favor of the exergame group. Furthermore, in the dual-center RCT, the exergame group improved walking. However, the effect sizes remained small. This may be due to the better functioning and health status of the participants. In the dual-center RCT, the participants' mean time in the TUG test at baseline was below 10 seconds, while longer times are considered to indicate poorer physical function (Bade et al., 2012). Additionally, participants in most of the studies accepted in the systematic review did not have major risks or illnesses affecting their health. A similar effect of participants' good functional and health status has been considered to be the reason for small effect sizes in earlier studies (Howes et al., 2017; Vázquez et al., 2018).

Previous studies investigating the effect of exergaming in older adults undergoing TKR revealed no statistically significant difference between the groups in the outcome variables measuring walking and mobility. In these studies, the duration of the interventions was a maximum of 6 weeks, while the duration in the systematic review (Study II) was 9 weeks and in the dual-center RCT (Study III) 16 weeks, respectively. In addition, in these previous studies, exergaming was adjunct to standard physiotherapy or standard exercise. This may indicate that better results can be achieved with longer-lasting interventions where game training is the primary form of training in the intervention group. The effect of the shorter interventions on the physical function was also speculated by Hadamus et al. (2021), who stated that a four-week intervention after TKR appears to be too short for significant improvements.

Overall, it is notable that it is possible to improve mobility and walking with exergame-based training, even though it is different in nature compared with more traditional exercising. That is, exergaming is usually performed in a more stationary manner than moving around, especially when standing in front of camera, which follows the movements and reactions of players. Therefore, exergaming brought something more, which is why participants achieved better results on outcomes measuring mobility and walking. The investigation of gaming experiences could bring more information in this regard.

6.3.1.1 Covariates' impact on the effects of exergaming on walking

In the systematic review (Study II), the study demonstrated expected results regarding the impact of covariates on the effects of exergaming on walking. When exergame-based intervention was compared with the inactive controls, the exergame group received more benefits than if the control group had been an active group. Similarly, in the study of Hai et al. (2022), who studied the effect of exergaming on physical function in older adults, the effect sizes were slightly bigger with an inactive group; however, the benefits were the same despite the group.

Other covariates studied, such as the study quality, participants' age and walking performance before the intervention, duration of the intervention, number of sessions per week, duration of one session, and the fact that the exercise was carried out unsupervised (setting) or that the technology used was developed for physical rehabilitation did not affect the effect size. Of these, the study of Hai et al. (2022) has shown similar results in terms of the study quality, setting, duration of one session, and participants' age, but not with the number of sessions per week. Hai et al. (2022) found out that when the frequency was moderate, i.e., 3-4 times weekly, it was associated with effect. In the current systematic review, 25.4% of the studies reported moderate frequency, most had low frequency (61.0%). Since Hai et al. (2022) did not report the proportions of frequencies, it is not possible to assess the difference.

Moreover, regarding the participants' age at the baseline, there is a contradiction with the study results of a previous systematic review (Vázquez et al., 2018) that studied the effect of exergaming on physical health and showed that exergaming was more beneficial for older participants. Vázquez et al. (2018) considered that this association may be related to lower physical, cognitive and emotional function in older adults. The average ages were similar in the studies included in the current systematic review (Study II) and in the systematic review of Vázquez et al. (2018). It is not possible to assess the cause for the difference in the covariate's impact in meta-regression analyses, especially when the cognitive and emotional function was not assessed in the current systematic review (Study II), and the baseline walking performance had no effect on the effect size.

6.3.2 Knee-related symptoms and physical function

In the dual-center RCT (Study III), both groups, i.e., those who exergamed and those who performed standard exercise, had positive changes in the knee-related symptoms and physical function assessed using the OKS. Change in both groups at four months was from a moderate to good state, suggesting normal recovery after the TKR. When the perceived pain was noted separately using the VAS-scale, a moderate to mild change was shown in both groups in the dual-center RCT as before. It can also be assumed that the rehabilitation of the participants in the feasibility study (Study I) at 10 weeks was in a good state, as they assessed in the WOMAC questionnaire and separately on the VAS-scale, that they had mild knee-related symptoms (pain and stiffness) and functional limitations. These participants followed the post-TKR standard exercise similarly like participants assigned to the standard exercise group in the dual-center RCT. Moreover, previous studies with patients with TKR has also shown an early decrease in the pain after TKR surgery in those patients who started exergaming (Hardt et al., 2018; Jin et al., 2018).

In the dual-center RCT (Study III), the change in OKS in both groups was also clinically significant, exceeding the estimate of minimal clinically important changes in the OKS (Beard et al., 2015). Moreover, the exergame group had already exceeded the score limit of OKS at four months, which is related to satisfaction with the TKR half a year after the surgery (Judge et al., 2012). This seems to be also confirmed by the results of the participants' satisfaction at 4 months; all the participants in the exergame group were either satisfied or very satisfied while some of the participants in the standard exercise group were unsatisfied or even very unsatisfied.

As the question was "How satisfied are you with the operated knee?", it did not emphasize any point of view that would have led participants to think about their satisfaction. That is why it is difficult to analyze the perspective with which the participants thought about and answered. It can be speculated that they evaluated their response from the perspective of knee-related symptoms and physical function. The differences in the answers could reflect, in addition to OKS, the exergame group's better performance in mobility and walking and the fact that in the exergame group, PA in leisure time, daily errands or commuting increased alongside intervention, while the same was not observed in the standard exercise group. Additionally, when the pain decreases, it may positively affect the physical ability and the quality of sleep, and thus improve the quality of life and affect the assessment of satisfaction with the operated knee (Alipourian et al., 2021; Hunter & Bierma-Zeinstra, 2019).

6.3.3 Lower extremity function

In the dual-center RCT (Study III), at 4 months, no intergroup changes between the exergame and standard exercise groups were observed in the active knee joint ROM measured with goniometer, in the lower extremity performance measured with the SPPB, and in the muscle strength measured with isometric knee extension and flexion force test. Participants in both groups showed an improvement from baseline only in the sit-to-stand test, i.e., in lower extremity muscle strength measured using the SPPB subtest. This is a promising result, as the sit-to-stand test specifically verifies the strength of the knee extensor muscles, the strengthening of which considerably affects walking (Capin et al., 2022), and is associated with better knee ROM (Pua et al., 2022).

When observing the results of knee ROM after the TKR, similar results were observed in participants in the dual-center RCT (Study III) and in the feasibility study (Study I). In the feasibility study, the participants had corresponding standard exercise protocol as the participants in the control group in the dual-center RCT. In both studies, these participants following standard exercise had equal knee flexion, the former at 10 weeks after the surgery and the latter at 16 weeks after the surgery. In the dual-center RCT, the knee ROM degrees remained below the baseline level. As the initial knee ROM before surgery was not known in the feasibility study, it can be only speculated that the knee flexion at 10 weeks might be similarly below that before surgery. This speculation is based on the previous results with knee flexion remaining below the pre-surgical level at 12 and even 24 weeks after TKR surgery (Bade et al., 2010). However, the knee extension in the participants in the dual-center RCT at 16 weeks after TKR was better in the standard exercise group as well as in the exergame group compared with knee extension in the participants in the feasibility study at 10 weeks after TKR. Similarly, in Bade et al. (2010), the participants already extended the operated knee 12 weeks after TKR. Perhaps in the future, in patients who have undergone TKR, more attention should be paid to early flexibility exercises to increase knee flexion, since it also has an effect on walking, especially in its stance phase (Kubota et al., 2022).

6.4 Methodological considerations

The novelty of this thesis was the investigation of the movement characteristics during exergaming and their comparison with the movements in standard exercises (the feasibility study, Study I), the consideration of the initial walking performance in the magnitude of the intervention effect on walking (the systematic review, Study II), the study of the effectiveness of long-term, independent exergame-based training at home on physical function and pain after TKR (the dual-center RCT, Study III), and the assessment of other PA in leisure time, daily errands, and commuting alongside exergaming, and standard exercising during the intervention period (Study III). The planning and implementation of the studies were based on solid practical and research expertise in the fields of physiotherapy, biomechanics, game technology, medicine, and statistics. Hence, the strengths were carefully designed and implemented studies, and valid and appropriate methods in instrumentation, data collection, and data analysis. In addition, the protocols of the systematic review and the dual-center RCT were registered before data collection, and all studies were conducted and reported in line with the guidelines (Higgins et al., 2022; Liberati et al., 2009; Moher et al., 2010; Orkin et al., 2021; Vandenbroucke et al., 2007), which further increases the certainty and quality of these studies.

For all studies included in the thesis, some limitations should be considered. A common limitation in all the studies was the small number of participants. In the feasibility study (Study I) and in the dual-center RCT (Study III), approximately half of the planned sample size was achieved. In the systematic review (Study II), despite the high pooled number of participants, there were mainly less than 20 participants in the experimental or comparison group per study. One reason may be the strict inclusion criteria regarding the characteristics of participants. For example, in the feasibility study and in the dual-center RCT, the participants had to be over 60 years old or from 60 to 75 years old, respectively, and TKR had to be related to the surgical treatment of OA, revisions were excluded. Also, the recruitment of subjects before TKR surgery, which can be a stressful situation alone for older adults, may affect the willingness to participate in the study. Moreover, in the dual-center RCT, part of the recruitment took place during the COVID-19 pandemic in 2020, which might have been affect not only the willingness but also the opportunities to participate in the study, especially due to the restrictions placed on older adults during that time. Elective TKR surgeries, which had already been scheduled or were about to be scheduled, were postponed due to the closure of hospital operations, and after lockdowns were over, older adults were recommended to leave from home only for compulsory events. The consequence for the dual-center RCT was that it remained unpowered, and it did not allow the generalization of the results.

Similarly, in the systematic review (Study II), the heterogeneity in interventions, type of comparison group, and outcomes measuring walking in included studies had an effect in the interpretation of the results. Despite the models used to correct this variation in the meta-analysis (the random effect model) and in the meta-regression (the multiple imputation model), it must be stated that no strong interpretation could be provided to the covariates' impact on the effect.

In the dual-center RCT (Study III), in addition to the constraints caused to the recruitment process, the COVID-19 pandemic caused limitations to data collection. Due to the placed restrictions, i.e., lockdowns and recommendation to avoid contacts outside family, some of the participants were not measured for outcomes that should have been collected with a physical test in close contact. However, this was taken into account in the analysis method of these outcomes and all outcomes collected by pen-and-paper could be collected from these participants by mail. Otherwise, it can be stated that the collection of tests and questionnaires measuring the physical function and pain was successful. Nevertheless, the most important issue in this partial interruption in data collection was, that participants of the dual-center RCT were able to continue their rehabilitation at home in the assigned group, i.e., continue exergaming or standard exercise, without their rehabilitation process being disturbed or stopped.

In addition, with respect to the limitations, the training sequence in the feasibility study (Study I) and the blinding of the assessors after baseline assessments in the dual-center RCT (Study III) should be mentioned. The test sessions in the feasibility study were not randomized, which meant that the participants performed the training in the same order, i.e., first the standard exercises and subsequently, the exergames. Performing the usual exercises first might affect gaming either positively or negatively by acting as a warm-up or causing stress and pain toward the end of the test session, although such effects were not found in the study. In the dual-center RCT, blinding of the assessors were not possible because of the game-specific questionnaires whose collection in the follow-up assessment visits was part of the protocol (Aartolahti et al., 2022). However, this limitation of the blinding process can be considered as minor, as there was no reason to believe that the knowledge of the intervention status could have influenced the outcome assessments.

6.5 Implications and future directions

This thesis showed important implications in the customization of exergames for use in the rehabilitation process of a certain group of older adults and about the effects of exergame-based training on physical function in older adults. First, this thesis brought certainty that exergames can be tailored to match standard exercises and thus, be a possible alternative for older adults over more traditional methods of exercise. Second, this thesis strengthened the previous knowledge that exergame-based training for the older adults is an effective training method for improving walking and mobility, also in unsupervised training at home.

Future research should focus on the factors that exert an effect on the adherence to therapeutic exercise with exergames and on the progression of therapeutic exercise with exergames. There is a lack of research on both in older adults, although both may have a significant impact on the rehabilitation outcomes, for example after TKR. Moreover, previously published studies revealed the lack of research on pre-operative exergaming in older adults undergoing TKR. This could be an interesting line of research to evaluate the effect of exergame-based pre-TKR intervention on the post-TKR rehabilitation outcomes, especially as the preoperative physical function of an individual is associated with better physical function 6 and 12 months after the TKR (Olsen et al., 2022).

When therapeutic exercise employing exergames is planned, it is important to know what the best method for individual would be to implement therapeutic exercise and thus, adhere to it (Kolasinski et al., 2020). This refers, for example, to the initial function of the individual before the rehabilitation process and the attitude of the rehabilitee towards exergaming. For example, in studies with cardiac rehabilitees, it has been considered that age and the functional level or the fact that the person has no previous experience with technology may influence on the adherence to exergaming or in using technology in remote rehabilitation (Alves da Cruz et al., 2022; Anttila et al., 2019). The individual may, for example, feel that their advanced age or lower functional ability may limit the use of exergames and therefore, favor standard exercising (Alves da Cruz et al., 2022) or they may fear that they are not skilled enough to use technology (Anttila et al., 2019). Notably, non-adherence to exergaming may simply be due to the reason that the person does not enjoy exercising with exergames (Oesch et al., 2017). In contrast, games can inspire older adults to exercise, for example, through the enjoyment they bring to exercise. These barriers and opportunities could be explored through the participants' characteristics, and their experience and perspectives of the technology and the exergame-based rehabilitation. Furthermore, game development in data collection could bring even more opportunities to evaluate and develop the individualization of rehabilitation. The results of these types of future study would clarify the connection of the mentioned issues to the adherence on exergame-based training and could give a broader picture of identification of individuals to whom exergame-based training would suit best. Thus, the results could help to find the individuals to whom exergame-based training could best be offered as an alternative to standard exercise.

Adequate dosing of therapeutic exercise is important when planning progressive rehabilitation programs and monitoring the effect of the program on rehabilitative outcomes. Monitoring of the implementation of the planned exercise dosage is difficult if not impossible, especially in unsupervised therapeutic exercises. The technology in the exergames makes it possible to collect the kinematic data, for example the volume and range of movement, during the exergame-based interventions. These movement characteristics could be the number of repetitions performed during the exergame with lateral weight transfers to the right and left and the degree of active knee ROM performed during the exergame with knee flexion movement. By analyzing the kinematics realized during exergame-based training, it can increase the understanding of the individual's rehabilitation process and provide more profound and required knowledge for design of progressive and possibly more effective exergame-based rehabilitation programs. Moreover, the kinematic data may be used not only after the intervention period for future development, but also already during the intervention. It could enable, for example, remote monitoring of unsupervised exergaming at home and thus enable physiotherapeutic guidance of the rehabilitee based on the progression of their rehabilitation process and thereby improve the implementation of home-based rehabilitation.

7 MAIN FINDINGS AND CONCLUSIONS

The main findings of this study can be summarized as follows:

1) Older adults with TKR can achieve similar individual ranges of motion of the knee during exergaming with games that are customized for rehabilitation after TKR surgery as with standard post-TKR exercises without increasing the strain and pain experienced during exergaming. During exergaming, the volume and intensity of movement are mostly higher compared with standard post-TKR exercising.

2) Exergame-based interventions are effective for the improvement of walking in older adults without neurological disorders compared with control with other exercise (active control) or no exercise (inactive control). Improvements in walking were maintained after a non-exergaming follow-up.

3) The strongest association regarding the effect of exergaming on walking was in the type of control group, i.e., whether the control group had other exercise (active control) or no exercise (inactive control). The exergame group gained more benefits when compared with inactive control. Otherwise, the association with the effect of exergaming was not seen in other intervention characteristics (the duration of intervention, setting of intervention, number of sessions per week, duration of single session, type of comparison group, and technology used), or in the participants' age and their baseline walking performance at baseline. Moreover, the high risk of bias among studies included in the meta-analysis had no association on the effect.

4) A progressive, 4-month exergaming with custom-made games is effective on improving the mobility in older adults with TKR compared with standard post-TKR exercise. In addition, early satisfaction with the operated knee was better in the exergame group. Knee related pain and

function, walking, knee joint ROM, lower extremity performance, and muscle strength improved equally in both groups.

In conclusion, the results of this study indicate that exergame-based training is an effective method for improving physical function, especially walking and mobility, and for decreasing pain in older adults in both supervised and unsupervised therapeutic exercise. Furthermore, the results indicate that it is possible to tailor exergames to achieve the movement characteristics of rehabilitation after TKR surgery without increasing the strain or pain during exercise. Physical therapists and other rehabilitation professionals may consider exergaming as a promising form of exercise for use in physical function and pain management in older adults as an alternative to standard exercise, and especially in the rehabilitation after TKR.

YHTEENVETO (SUMMARY IN FINNISH)

Liikuntapelit ikääntyvien aikuisten kuntoutuksessa erityisesti polven tekonivelleikkauksen jälkeen

Liiketunnistukseen perustuvien liikuntapelien (exergames) käyttö ja tutkimus ikääntyvien aikuisten kuntoutuksessa on kasvanut. Tutkimustieto liikuntapelien vaikutuksesta kävelyyn ikääntyneillä aikuisilla, joilla ei ole toiminnanrajoitteita, on kuitenkin vähäistä. Myös ortopedisilla potilailla liikuntapelien vaikutuksia fyysiseen toimintakykyyn ja kipuun on tutkittu vähän. Lisäksi tutkimusta, jossa liikuntapeleissä tehtävien liikkeiden ominaisuuksia verrataan vastaaviin tavanomaisessa harjoittelussa käytettyihin, ei ole julkaistu. Näyttöä liikeominaisuuksien toteutumisesta pelaamisen aikana sekä liikuntapelien käytön vaikutuksista fyysiseen toimintakykyyn ja kivun kokemiseen tarvitaan lisää.

Tämä väitöskirjatutkimus on osa Business Ecosystems in Effective Exergaming -hanketta, jossa tutkittiin eri pelipohjaisten menetelmien käytettävyyttä ja vaikutuksia kuntoutusprosesseissa. Tämän väitöskirja-tutkimuksen tavoitteena oli tutkia liikuntapelien käytön vaikuttavuutta fyysiseen toimintakykyyn ja kivun kokemiseen ikääntyvillä henkilöillä, joilla ei ole neurologisia sairauksia ja heillä, joille oli tehty polven tekonivelleikkaus. Lisäksi tavoitteena oli selvittää polven tekonivelleikkauksen jälkeiseen kuntoutukseen mukautettujen liikuntapelien käytettävyyttä polven tekonivelleikkauksen jälkeisessä kuntoutuksessa tutkimalla harjoittelun aikana toteutuneita liikeominaisuuksia.

Poikkileikkaustutkimuksella tutkittiin, millaisia liikuntapelien harjoitteet olivat liikeominaisuuksiltaan verrattuna tavanomaisiin, polven tekonivelleikkauksen jälkeisiin kotiharjoitteisiin. Tutkitut liikeominaisuudet olivat liikkeen määrä (kesto, toistot), liikelaajuus (polvinivel) ja intensiteetti (kulmanopeus, kulmakertymä, resultanttivoima). Seitsemän henkilöä (keski-ikä 65 vuotta), joiden polven tekonivelleikkauksesta oli kulunut enintään neljä kuukautta, osallistui yhteen, yksilöllisesti järjestettyyn tutkimuskäyntiin liikuntalaboratoriolla. Tutkittavat täyttivät Western Ontario and McMaster Universities Osteoarthritis index -toimintakykykyselyn ja heiltä mitattiin leikatun polven liikelaajuus, jonka jälkeen he suorittivat tavanomaiset kotiharjoitukset (n=10) ja pelasivat liikuntapelit (n=10). Tavanomaisista kotiharjoitusliikkeistä videoitiin kolme (polven ojennusharjoitus istuen sekä polven koukistusharjoitus istuen ja seisten) ja liikuntapeleistä videoitiin viisi (2 polven ojennuspeliä istuen, polven koukistuspeli seisten ja 2 kyykkäyspeliä). Resultanttivoima mitattiin voimalevyillä seisten kahden painonsiirtopelin aikana. Lisäksi tutkittavilta kysyttiin harjoittelun ja pelaamisen aikaisesta koetusta rasituksesta ja kivusta. Tutkimuksen tulokset osoittivat, että tutkittavat saavuttivat yksilöllisesti mitatun liikelaajuuden liikuntapelien ja tavanomaisten harjoitusten aikana, mutta liikkeiden volyymi ja intensiteetti olivat enimmäkseen korkeampia liikuntapelien aikana. Harjoittelun aikainen koettu rasitus ja kipu oli vähäistä.

Systemaattisella kirjallisuuskatsauksella ja meta-analyysilla tutkittiin liikuntapelien käytön vaikuttavuutta kävelyyn verrattuna muuhun harjoitteluun (aktiivinen) tai siihen, että ei harjoiteltu (inaktiivinen) henkilöillä, joilla ei ole neurologisia sairauksia. Katsaukseen hyväksyttiin 66 satunnaistettua kontrolloitua tutkimusta (n=3797, keski-ikä 74 vuotta), joista 58 sisällytettiin meta-analyysiin. Näistä meta-analyysiin sisällytetyistä tutkimuksista 13:ssa oli seurantajakso, joka ei sisältänyt harjoittelua. Lisäksi meta-analyysiin sisällytettyjen tutkimusten kovariaattien yhteyttä meta-analyysin tulokseen selvitettiin metaregressioanalyysillä. Tutkitut kovariaatit olivat tutkittavien ikä ja lähtötason kävely, harjoitteluinterventioiden ominaisuudet, kuten niiden kesto ja vertailuryhmän tyyppi (aktiivinen/inaktiivinen) sekä tutkimuksiin liittyvä korkean harhan riski. Tutkimuksen tulokset osoittivat, että verrattuna aktiiviseen tai inaktiiviseen ryhmään, kävely parani tilastollisesti merkitsevästi enemmän liikuntapeleillä toteutuneessa valvotussa tai itsenäisesti suoritetussa harjoittelussa. Lisäksi liikuntapeliharjoittelun vaikutus kävelyyn säilyi seurantajaksolla. Vertailuryhmän harjoittelun tyypillä (aktiivinen/inaktiivinen) oli vahvin yhteys liikuntapelien vaikutuksen suuruuteen kävelyn paranemisessa.

Neljä kuukautta kestäneessä satunnaistetussa kontrolloidussa interventiotutkimuksessa tutkittiin kotiharjoitteluna toteutuneen peliharjoittelun vaikuttavuutta useaan fyysisen toimintakyvyn osa-alueeseen sekä kivun kokemiseen polven tekonivelleikkauksen jälkeen verrattuna tavanomaiseen, polven tekonivelleikkauksen jälkeiseen kotiharjoitteluun. Tutkimuksessa käytettiin aiemmassa liikeominaisuuksia tutkineessa poikkileikkaustutkimuksessa olleita liikuntapelejä. Tutkimukseen osallistui 52 henkilöä (keski-ikä 66 vuotta), jotka satunnaistettiin interventioryhmään (n=25) ja kontrolliryhmään (n=27). Interventioryhmä pelasi liikuntapelejä ja kontrolliryhmä teki tavanomaista harjoittelua sairaalasta kotiuduttuaan. Fyysistä toimintakykyä ja kipua mitattiin ennen leikkausta ja 2 ja 4 kuukautta leikkauksen jälkeen. Päätulosmuuttujina olivat polveen liittyviä oireita ja toimintakykyä mittaava Oxford Knee Score -kysely ja liikkumiskykyä mittaava Timed Up and Go -testi. Lisäksi mitattiin kävelynopeus, leikatun polven liikelaajuus, alaraajojen suorituskyky ja lihasvoima sekä polveen liittyvä kipu. Tutkittavilta kysyttiin myös tyytyväisyys leikattuun polveen ja heiltä mitattiin intervention aikainen sitoutuminen harjoitteluun ja muu fyysinen aktiivisuus, kuten harrastuksiin osallistuminen. Tutkimuksen tulokset osoittivat, että liikkumiskyky parani tilastollisesti merkitsevästi enemmän peliharjoitteluryhmässä kahden ja neljän kuukauden kohdalla verrattuna tavanomaiseen kotiharjoitteluun. Polveen liittyviä oireita ja toimintakykyä mittaavassa kyselyssä, muissa fyysistä toimintakykyä ja kipua mittaavissa tulosmuuttujissa ja harjoittelumäärässä ei ollut ryhmien välillä tilastollisesti merkitsevää eroa neljän kuukauden aikana. Interventiojakson aikana muu fyysinen aktiivisuus oli peliryhmässä korkeampi kahden viimeisen kuukauden aikana verrattuna ensimmäiseen kahteen kuukauteen. Neljän kuukauden kohdalla peliryhmässä 100 % ja tavanomaisen harjoittelun ryhmässä 74 % oli tyytyväisiä leikattuun polveen.

Yhteenvetona voidaan todeta, että fyysinen toimintakyky, erityisesti kävely ja liikkumiskyky paranevat ikääntyneillä aikuisilla ja tekonivelleikkauksen jälkeisessä kuntoutuksessa, jossa käytetään liikuntapelejä ohjatusti tai itsenäisenä harjoitteluna. Lisäksi liikuntapelejä voidaan mukauttaa saavuttamaan polven tekonivelleikkauksen jälkeiseen kuntoutukseen sopivat liikeharjoitteluominaisuudet. Liikuntapelejä voidaan pitää lupaavana harjoittelumuotona ikääntyneiden henkilöiden toimintakyvyn parantamisessa ja kivun hallinnassa vaihtoehtona muulle harjoittelulle erityisesti polven tekonivelleikkauksen jälkeisessä kuntoutuksessa.

REFERENCES

Aartolahti, E., Janhunen, M., Katajapuu, N., Paloneva, J., Pamilo, K., Keemu, H., Karvonen, M., Luimula, M., Korpelainen, R., Jämsä, T., Mäkelä, K., & Heinonen, A. (2022). Effectiveness of gamification in knee replacement rehabilitation: Protocol for a randomized controlled trial (BEE-RCT) with a qualitative approach. *JMIR Research Protocols*, *11*(11), e38434. https://doi.org/10.2196/38434

Ackerman, I. N., Bohensky, M. A., Zomer, E., Tacey, M., Gorelik, A., Brand, C. A., & de Steiger, R. (2019). The projected burden of primary total knee and hip replacement for osteoarthritis in Australia to the year 2030. *BMC Musculoskeletal Disorders*, *20*, 90. https://doi.org/10.1186/s12891-019-2411-9

Ainsworth, B. E., Haskell, W. L., Herrmann, S. D., Meckes, N., Bassett, D. R., Tudor-Locke, C., Greer, J. L., Vezina, J., Whitt-Glover, M. C., & Leon, A. S. (2011). 2011 compendium of physical activities: A second update of codes and MET values. *Medicine & Science in Sports & Exercise*, *43*(8), 1575–1581. https://doi.org/10.1249/MSS.0b013e31821ece12

Alipourian, A., Farhadian, N., Zereshki, E., & Khazaie, H. (2021). Improvement of sleep quality 6 months after total knee arthroplasty: A systematic review and meta-analysis. *Journal of Orthopaedic Surgery and Research*, *16*, 342. https://doi.org/10.1186/s13018-021-02493-4

Altorfer, P., Adcock, M., de Bruin, E. D., Graf, F., & Giannouli, E. (2021). Feasibility of cognitive-motor exergames in geriatric inpatient rehabilitation: A pilot randomized controlled study. *Frontiers in Aging Neuroscience*, *13*, 739948. https://doi.org/10.3389/fnagi.2021.739948

Alves da Cruz, M. M., Grigoletto, I., Ricci-Vitor, A. L., da Silva, J. M., Franco, M. R., & Vanderlei, L. C. M. (2022). Perceptions and preferences of patients with cardiac conditions to the inclusion of virtual reality-based therapy with conventional cardiovascular rehabilitation: A qualitative study. *Brazilian Journal of Physical Therapy*, *26*(3), 100419. https://doi.org/10.1016/j.bjpt.2022.100419

Anttila, M.-R., Kivistö, H., Piirainen, A., Kokko, K., Malinen, A., Pekkonen, M., & Sjögren, T. (2019). Cardiac rehabilitees' technology experiences before remote rehabilitation: Qualitative study using a grounded theory approach. *Journal of Medical Internet Research*, *21*(2), e10985. https://doi.org/10.2196/10985

Artz, N., Elvers, K. T., Lowe, C. M., Sackley, C., Jepson, P., & Beswick, A. D. (2015). Effectiveness of physiotherapy exercise following total knee replacement: Systematic review and meta-analysis. *BMC Musculoskeletal Disorders*, *16*, 15. https://doi.org/10.1186/s12891-015-0469-6

Babatunde, O. O., Jordan, J. L., Van der Windt, D. A., Hill, J. C., Foster, N. E., & Protheroe, J. (2017). Effective treatment options for musculoskeletal pain in primary care: A systematic overview of current evidence. *PLOS ONE*, *12*(6), e0178621. https://doi.org/10.1371/journal.pone.0178621

Bacha, J. M. R., Gomes, G. C. V., de Freitas, T. B., Viveiro, L. A. P., da Silva, K. G., Bueno, G. C., Varise, E. M., Torriani-Pasin, C., Alonso, A. C., Luna, N. M. S., D'Andrea Greve, J. M., & Pompeu, J. E. (2018). Effects of kinect adventures games versus conventional physical therapy on postural control in elderly people: A randomized controlled trial. *Games for Health Journal*, *7*, 24–36. https://doi.org/10.1089/g4h.2017.0065

Bade, M. J., Kohrt, W. M., & Stevens-Lapsley, J. E. (2010). Outcomes before and after total knee arthroplasty compared to healthy adults. *Journal of Orthopaedic & Sports Physical Therapy*, *40*(9), 559–567. https://doi.org/10.2519/jospt.2010.3317

Bade, M. J., Wolfe, P., Zeni, J. A., Stevens-Lapsley, J. E., & Snyder-Mackler, L. (2012). Predicting poor physical performance after total knee arthroplasty. *Journal of Orthopaedic Research*, *30*(11), 1805–1810. https://doi.org/10.1002/jor.22140

Bakaa, N., Chen, L. H., Carlesso, L., Richardson, J., & Macedo, L. (2021). Reporting of post-operative rehabilitation interventions for Total knee arthroplasty: A scoping review. *BMC Musculoskeletal Disorders*, *22*, 602. https://doi.org/10.1186/s12891-021-04460-w

Beard, D. J., Harris, K., Dawson, J., Doll, H., Murray, D. W., Carr, A. J., & Price, A. J. (2015). Meaningful changes for the Oxford hip and knee scores after joint replacement surgery. *Journal of Clinical Epidemiology*, *68*, 73–79. https://doi.org/10.1016/j.jclinepi.2014.08.009

Borg, G. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377–381.

Briggs, A. M., Cross, M. J., Hoy, D. G., Sànchez-Riera, L., Blyth, F. M., Woolf, A. D., & March, L. (2016). Musculoskeletal health conditions represent a global threat to healthy aging: A report for the 2015 World Health Organization World report on ageing and health. *The Gerontologist*, *56*(S2), S243–S255. https://doi.org/10.1093/geront/gnw002

Brown, O. S., Hu, L., Demetriou, C., Smith, T. O., & Hing, C. B. (2020). The effects of kinesiophobia on outcome following total knee replacement: A systematic review. *Archives of Orthopaedic and Trauma Surgery*, *140*(12), 2057–2070. https://doi.org/10.1007/s00402-020-03582-5

Buhagiar, M. A., Naylor, J. M., Harris, I. A., Xuan, W., Adie, S., & Lewin, A. (2019). Assessment of outcomes of inpatient or clinic-based vs home-based rehabilitation after total knee arthroplasty: A systematic review and meta-analysis. *JAMA Network Open*, *2*(4), e192810. https://doi.org/10.1001/jamanetworkopen.2019.2810

Cano Porras, D., Siemonsma, P., Inzelberg, R., Zeilig, G., & Plotnik, M. (2018). Advantages of virtual reality in the rehabilitation of balance and gait: Systematic review. *Neurology*, *90*(22), 1017–1025. https://doi.org/10.1212/WNL.0000000000005603

Capin, J. J., Bade, M. J., Jennings, J. M., Snyder-Mackler, L., & Stevens-Lapsley, J. E. (2022). Total knee arthroplasty assessments should include strength and performance-based functional tests to complement range-of-motion and patient-reported outcome measures. *Physical Therapy*, *102*(6), pzac033. https://doi.org/10.1093/ptj/pzac033

Caspersen, C. J., Powell, K. E., & Christenson, G. M. (1985). Physical activity, exercise, and physical fitness: Definitions and distinctions for health-related research. *Public Health Reports*, *100*(2), 126–131.

Chan, E. Y., Blyth, F. M., Nairn, L., & Fransen, M. (2013). Acute postoperative pain following hospital discharge after total knee arthroplasty. *Osteoarthritis and Cartilage*, *21*(9), 1257–1263. https://doi.org/10.1016/j.joca.2013.06.011

Chan, W. L. S., & Pin, T. W. (2019). Reliability, validity and minimal detectable change of 2-minute walk test, 6-minute walk test and 10-meter walk test in frail older adults with dementia. *Experimental Gerontology*, *115*, 9–18. https://doi.org/10.1016/j.exger.2018.11.001

Christensen, J. C., Paxton, R. J., Baym, C., Forster, J. E., Dayton, M. R., Hogan, C. A., & Stevens-Lapsley, J. E. (2020). Benefits of direct patient discharge to outpatient physical therapy after total knee arthroplasty. *Disability and Rehabilitation*, *42*(5), 660–666. https://doi.org/10.1080/09638288.2018.1505968

Christensen, J. C., Pelt, C. E., Bo Foreman, K., LaStayo, P. C., Anderson, A. E., Gililland, J. M., & Mizner, R. L. (2021). Longitudinal study of knee load avoidant movement behavior after total knee arthroplasty with recommendations for future retraining interventions. *The Knee*, *30*, 90–99. https://doi.org/10.1016/j.knee.2021.03.014

Christiansen, C. L., Bade, M. J., Davidson, B. S., Dayton, M. R., & Stevens-Lapsley, J. E. (2015). Effects of weight-bearing biofeedback training on functional movement patterns following total knee arthroplasty: A randomized controlled trial. *The Journal of Orthopaedic and Sports Physical Therapy*, *45*(9), 647–655. https://doi.org/10.2519/jospt.2015.5593

Christopher, A., Kraft, E., Olenick, H., Kiesling, R., & Doty, A. (2021). The reliability and validity of the Timed Up and Go as a clinical tool in individuals with and without disabilities across a lifespan: A systematic review: Psychometric properties of the Timed Up and Go. *Disability and Rehabilitation*, *43*(13), 1799–1813. https://doi.org/10.1080/09638288.2019.1682066

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). Lawrence Erlbaum.

Collado-Mateo, D., Lavín-Pérez, A. M., Peñacoba, C., Del Coso, J., Leyton-Román, M., Luque-Casado, A., Gasque, P., Fernández-del-Olmo, M. Á., & Amado-Alonso, D. (2021). Key factors associated with adherence to physical exercise in patients with chronic diseases and older adults: An umbrella review. *International Journal of Environmental Research and Public Health*, *18*(4), 2023. https://doi.org/10.3390/ijerph18042023 de Vries, A. W., Faber, G., Jonkers, I., van Dieen, J. H., & Verschueren, S. M. P. (2018). Virtual reality balance training for elderly: Similar skiing games elicit different challenges in balance training. *Gait & Posture*, *59*, 111–116. https://doi.org/10.1016/j.gaitpost.2017.10.006

Delbroek, T., Vermeylen, W., & Spildooren, J. (2017). The effect of cognitive-motor dual task training with the biorescue force platform on cognition, balance and dual task performance in institutionalized older adults: A randomized controlled trial. *Journal of Physical Therapy Science*, *29*(7), 1137–1143. https://doi.org/10.1589/jpts.29.1137

Deterding, S., Dixon, D., Khaled, R., & Nacke, L. (2011). *From game design elements to gamefulness: Defining "gamification"*. MindTrek '11: Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments, Tampere, Finland. https://doi.org/10.1145/2181037.2181040

Doma, K., Grant, A., & Morris, J. (2018). The effects of balance training on balance performance and functional outcome measures following total knee arthroplasty: A systematic review and meta-analysis. *Sports Medicine*, *48*(10), 2367–2385. https://doi.org/10.1007/s40279-018-0964-7

Doyle, J., Kelly, D., Patterson, M., & Caulfield, B. (2011, June). *The effects of visual feedback in therapeutic exergaming on motor task accuracy*. 2011 International Conference on Virtual Rehabilitation (ICVR), Zurich, Switzerland. https://doi.org/10.1109/ICVR.2011.5971821

Fitzgerald, D., Foody, J., Kumar, D., Kelly, D., Ward, T., Markham, C., & Caulfield, B. (2006). *Integration of kinematic analysis into computer games for exercise*. Proceedings of CGAMES 2006 - 9th International Conference on Computer Games: Artificial Intelligence and Mobile Systems, Dublin, Ireland. https://www.cp.eng.chula.ac.th/~vishnu/conferences/CGAMES06DublinePro.pdf

Fung, V., Ho, A., Shaffer, J., Chung, E., & Gomez, M. (2012). Use of Nintendo Wii Fit TM in the rehabilitation of outpatients following total knee replacement: A preliminary randomised controlled trial. *Physiotherapy*, *98*(3), 183–188. https://doi.org/10.1016/j.physio.2012.04.001

Gazendam, A., Zhu, M., Chang, Y., Phillips, S., & Bhandari, M. (2022). Virtual reality rehabilitation following total knee arthroplasty: A systematic review and meta-analysis of randomized controlled trials. *Knee Surgery, Sports Traumatology, Arthroscopy*, *30*(8), 2548–2555. https://doi.org/10.1007/s00167-022-06910-x

Giggins, O. M., Persson, U. M., & Caulfield, B. (2013). Biofeedback in rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, *10*, 60. https://doi.org/10.1186/1743-0003-10-60

Gogia, P. P., Braatz, J. H., Rose, S. J., & Norton, B. J. (1987). Reliability and validity of goniometric measurements at the knee. *Physical Therapy*, *67*(2), 192–195. https://doi.org/10.1093/ptj/67.2.192

Gokeler, A., Bisschop, M., Myer, G. D., Benjaminse, A., Dijkstra, P. U., van Keeken, H. G., van Raay, J. J. A. M., Burgerhof, J. G. M., & Otten, E. (2016). Immersive virtual reality improves movement patterns in patients after ACL reconstruction: Implications for enhanced criteria-based return-to-sport rehabilitation. *Knee Surgery, Sports Traumatology, Arthroscopy*, *24*(7), 2280–2286. https://doi.org/10.1007/s00167-014-3374-x

Gomes, G. C. V., Simões, M. do S., Lin, S. M., Bacha, J. M. R., Viveiro, L. A. P., Varise, E. M., Carvas Junior, N., Lange, B., Jacob Filho, W., & Pompeu, J. E. (2018). Feasibility, safety, acceptability, and functional outcomes of playing Nintendo Wii Fit PlusTM for frail older adults: A randomized feasibility clinical trial. *Maturitas*, *118*, 20–28. https://doi.org/10.1016/j.maturitas.2018.10.002

Gschwind, Y. J., Eichberg, S., Ejupi, A., de Rosario, H., Kroll, M., Marston, H. R., Drobics, M., Annegarn, J., Wieching, R., Lord, S. R., Aal, K., Vaziri, D., Woodbury, A., Fink, D., & Delbaere, K. (2015). ICT-based system to predict and prevent falls (iStoppFalls): Results from an international multicenter randomized controlled trial. *European Review of Aging and Physical Activity*, *12*(1), 10. https://doi.org/10.1186/s11556-015-0155-6

Guralnik, J. M., Simonsick, E. M., Ferrucci, L., Glynn, R. J., Berkman, L. F., Blazer, D. G., Scherr, P. A., & Wallace, R. B. (1994). A Short Physical Performance Battery assessing lower extremity function: Association with self-reported disability and prediction of mortality and nursing home. *Journal of Gerontology*, *49*(2), 85–94. https://doi.org/10.1093/geronj/49.2.m85

Hadamus, A., Bialoszewski, D., Blazkiewicz, M., Kowalska, A. J., Urbaniak, E., Wydra, K. T., Wiaderna, K., Boratynski, R., Kobza, A., & Marczynski, W. (2021). Assessment of the effectiveness of rehabilitation after total knee replacement surgery using sample entropy and classical measures of body balance. *Entropy*, *23*(2), 164. https://doi.org/10.3390/e23020164

Hai, L., Hou, H.-Y., Zhou, C., & Li, H.-J. (2022). The effect of exergame training on physical functioning of healthy older adults: A meta-analysis. *Games for Health Journal*, *11*(4), 207–224. https://doi.org/10.1089/g4h.2021.0173

Hardt, S., Schulz, M. R. G., Pfitzner, T., Wassilew, G., Horstmann, H., Liodakis, E., & Weber-Spickschen, T. S. (2018). Improved early outcome after TKA through an app-based active muscle training programme—A randomized-controlled trial. *Knee Surgery, Sports Traumatology, Arthroscopy*, *26*(11), 3429–3437. https://doi.org/10.1007/s00167-018-4918-2

Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, L., Li, T., Page, M. J., & Welch, V. A. (Eds.). (2022). *Cochrane handbook for systematic reviews of interventions* (version 6.3). Cochrane. www.training.cochrane.org/handbook

Hong, S., & Lee, G. (2019). Effects of an immersive virtual reality environment on muscle strength, proprioception, balance, and gait of a middle-aged woman who had total knee replacement: A case report. *The American Journal of Case Reports*, *20*(101489566), 1636–1642. https://doi.org/10.12659/AJCR.918521
Hospital Nova. (2020). *Opas polven tekonivelleikkaukseen tulevalle* [Guidebook for knee replacement patients].
Howes, S. C., Charles, D. K., Marley, J., Pedlow, K., & McDonough, S. M. (2017). Gaming for health: Systematic review and meta-analysis of the physical and cognitive effects of active computer gaming in older adults. *Physical Therapy*, *97*(12), 1122–1137. https://doi.org/10.1093/ptj/pzx088
Hunter, D. J., & Bierma-Zeinstra, S. (2019). Osteoarthritis. *The Lancet*, *393*(10182), 1669–1772. https://doi.org/10.1016/S0140-6736(19)30417-9
Hunter, D. J., McDougall, J. J., & Keefe, F. J. (2008). The symptoms of osteoarthritis and the genesis of pain. *Rheumatic Disease Clinics of North America*, *34*(3), 623–643. https://doi.org/10.1016/j.rdc.2008.05.004
Ismail, N. A., Hashim, H. A., & Ahmad Yusof, H. (2022). Physical activity and exergames among older adults: A scoping review. *Games for Health Journal*, *11*, 1–17. https://doi.org/10.1089/g4h.2021.0104
Jansson, J., Laukka, E., Kanste, O., Koivisto, J., & Jansson, M. (2022). Identified gamification opportunities for digital patient journey solution during an arthroplasty journey: Secondary analysis of patients' interviews. *Nursing Open*, *9*(4), 2044–2053. https://doi.org/10.1002/nop2.1215
Jensen, M. P., Chen, C., & Brugger, A. M. (2003). Interpretation of visual analog scale ratings and change scores: A reanalysis of two clinical trials of postoperative pain. *The Journal of Pain*, *4*(7), 407–414. https://doi.org/10.1016/s1526-5900(03)00716-8
Jette, D. U., Hunter, S. J., Burkett, L., Langham, B., Logerstedt, D. S., Piuzzi, N. S., Poirier, N. M., Radach, L. J. L., Ritter, J. E., Scalzitti, D. A., Stevens-Lapsley, J. E., Tompkins, J., Zeni Jr, J., for the American Physical Therapy Association. (2020). Physical therapist management of total knee arthroplasty. *Physical Therapy*, *100*(9), 1603–1631. https://doi.org/10.1093/ptj/pzaa099
Jin, C., Feng, Y., Ni, Y., & Shan, Z. (2018). Virtual reality intervention in postoperative rehabilitation after total knee arthroplasty: A prospective and randomized controlled clinical trial. *International Journal of Clinical and Experimental Medicine*, *11*(6), 6119–6124. ijcem0067965.pdf
Judge, A., Arden, N. K., Kiran, A., Price, A., Javaid, M. K., Beard, D., Murray, D., & Field, R. E. (2012). Interpretation of patient-reported outcomes for hip and knee replacement surgery: Identification of thresholds associated with satisfaction with surgery. *The Journal of Bone and Joint Surgery. British Volume*, *94-B*, 412–418. https://doi.org/10.1302/0301-620X.94B3.27425
Kato, P. M. (2010). Video games in health care: Closing the gap. *Review of General Psychology*, *14*(2), 113–121. https://doi.org/10.1037/a0019441

Katz, P., O'Grady, M., Davis, G. C., Rojas-Fernandez, C., Ferrell, B., Levy, R., Neiman, D. C., Young, M. A., Radcliff, S., Reitt, B. B., Prassas, A., & Lundebjerg, N. (2001). Exercise prescription for older adults with osteoarthritis pain: Consensus practice recommendations. A supplement to the AGS clinical practice guidelines on the management of chronic pain in older adults. *Journal of the American Geriatrics Society*, *49*(6), 808–823. https://doi.org/10.1046/j.1532-5415.2001.00496.x

Kenward, M. G., & Roger, J. H. (1997). Small sample inference for fixed effects from restricted maximum likelihood. *Biometrics*, *53*(3), 983–997. https://doi.org/10.2307/2533558

Kolasinski, S. L., Neogi, T., Hochberg, M. C., Oatis, C., Guyatt, G., Block, J., Callahan, L., Copenhaver, C., Dodge, C., Felson, D., Gellar, K., Harvey, W. F., Hawker, G., Herzig, E., Kwoh, C. K., Nelson, A. E., Samuels, J., Scanzello, C., White, D., … Reston, J. (2020). 2019 American College of Rheumatology/Arthritis Foundation guideline for the management of osteoarthritis of the hand, hip, and knee. *Arthritis Care & Research*, *72*(2), 149–162. https://doi.org/10.1002/acr.24131

Kubota, M., Kokubo, Y., Miyazaki, T., Matsuo, H., Naruse, H., Shouji, K., Shimada, S., & Matsumine, A. (2022). Effects of knee extension exercise starting within 4 h after total knee arthroplasty. *European Journal of Orthopaedic Surgery & Traumatology*, *32*(5), 803–809. https://doi.org/10.1007/s00590-021-03042-9

Lee, J., Chang, R. W., Ehrlich-Jones, L., Kwoh, C. K., Nevitt, M., Semanik, P. A., Sharma, L., Sohn, M.-W., Song, J., & Dunlop, D. D. (2015). Sedentary behavior and physical function: Objective evidence from the osteoarthritis initiative. *Arthritis Care & Research*, *67*(3), 366–373. https://doi.org/10.1002/acr.22432

Lee, M., Suh, D., Son, J., Kim, J., Eun, S.-D., & Yoon, B. (2016). Patient perspectives on virtual reality-based rehabilitation after knee surgery: Importance of level of difficulty. *Journal of Rehabilitation Research and Development*, *53*(2), 239–252. https://doi.org/10.1682/JRRD.2014.07.0164

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. *PLoS Medicine*, *6*(7), e1000100. https://doi.org/10.1371/journal.pmed.1000100

Matallaoui, A., Koivisto, J., Hamari, J., & Zarnekow, R. (2017). *How effective is "Exergamification"? A systematic review on the effectiveness of gamification features in exergames*. Proceedings of the 50th Hawaii International Conference on System Sciences, Waikoloa, USA. http://hdl.handle.net/10125/41560

McConnell, S., Kolopack, P., & Davis, A. M. (2001). The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC): A review of its utility and measurement properties. *Arthritis & Rheumatism*, *45*(5), 453–461. https://doi.org/10.1002/1529-0131(200110)45:5<453::AID-ART365>3.0.CO;2-W

McKenzie, J. E., Brennan, S. E., Ryan, R. E., Thomson, H. J., Johnston, R. V., & Thomas, J. (2022). Chapter 3: Defining the criteria for including studies and how they will be grouped for the synthesis. In J. P. T. Higgins, J. Thomas, J. Chandler, M. Cumpston, T. Li, M. J. Page & V. A. Welch (Eds.), *Cochrane Handbook for Systematic Reviews of Interventions (version 6.3)*. Cochrane. https://training.cochrane.org/handbook

Mete, E., & Sari, Z. (2022). The efficacy of exergaming in patients with knee osteoarthritis: A randomized controlled clinical trial. *Physiotherapy Research International*, *27*(3), 1–11. https://doi.org/10.1002/pri.1952

Mistry, J., Elmallah, R., Bhave, A., Chughtai, M., Cherian, J., McGinn, T., Harwin, S., & Mont, M. (2016). Rehabilitative guidelines after total knee arthroplasty: A review. *Journal of Knee Surgery*, *29*(03), 201–217. https://doi.org/10.1055/s-0036-1579670

Mizner, R. L., Petterson, S. C., & Snyder-Mackler, L. (2005). Quadriceps strength and the time course of functional recovery after total knee arthroplasty. *Journal of Orthopaedic & Sports Physical Therapy*, *35*(7), 424–436. https://doi.org/10.2519/jospt.2005.35.7.424

Moher, D., Hopewell, S., Schulz, K. F., Montori, V., Gotzsche, P. C., Devereaux, P. J., Elbourne, D., Egger, M., & Altman, D. G. (2010). CONSORT 2010 explanation and elaboration: Updated guidelines for reporting parallel group randomised trials. *BMJ*, *340*, c869. https://doi.org/10.1136/bmj.c869

National Committee on Vital and Health Statistics. (2001). *Classifying and reporting functional status*. https://www.ncvhs.hhs.gov/wp-content/uploads/2017/08/010617rp.pdf

Niemeläinen, M., Mäkelä, K. T., Robertsson, O., W-Dahl, A., Furnes, O., Fenstad, A. M., Pedersen, A. B., Schrøder, H. M., Huhtala, H., & Eskelinen, A. (2017). Different incidences of knee arthroplasty in the Nordic countries: A population-based study from the Nordic Arthroplasty Register Association. *Acta Orthopaedica*, *88*(2), 173–178. https://doi.org/10.1080/17453674.2016.1275200

Oesch, P., Kool, J., Fernandez-Luque, L., Brox, E., Evertsen, G., Civit, A., Hilfiker, R., & Bachmann, S. (2017). Exergames versus self-regulated exercises with instruction leaflets to improve adherence during geriatric rehabilitation: A randomized controlled trial. *BMC Geriatrics*, *17*, 77. https://doi.org/10.1186/s12877-017-0467-7

Olsen, U., Lindberg, M. F., Rose, C., Denison, E., Gay, C., Aamodt, A., Brox, J. I., Skare, Ø., Furnes, O., Lee, K., & Lerdal, A. (2022). Factors correlated with physical function 1 year after total knee arthroplasty in patients with knee osteoarthritis: A systematic review and meta-analysis. *JAMA Network Open*, *5*(7), e2219636. https://doi.org/10.1001/jamanetworkopen.2022.19636

Ong, D. S. M., Weibin, M. Z., & Vallabhajosyula, R. (2021). Serious games as rehabilitation tools in neurological conditions: A comprehensive review. *Technology and Health Care*, *29*, 15–31. https://doi.org/10.3233/THC-202333

Orkin, A. M., Gill, P. J., Ghersi, D., Campbell, L., Sugarman, J., Emsley, R., Steg, P. G., Weijer, C., Simes, J., Rombey, T., Williams, H. C., Wittes, J., Moher, D., Richards, D. P., Kasamon, Y., Getz, K., Hopewell, S., Dickersin, K., Wu, T., … Concato, J. (2021). Guidelines for reporting trial protocols and completed trials modified due to the COVID-19 pandemic and other extenuating circumstances: The CONSERVE 2021 statement. *JAMA*, *326*(3), 257–265. https://doi.org/10.1001/jama.2021.9941

Pacheco, T. B. F., de Medeiros, C. S. P., de Oliveira, V. H. B., Vieira, E. R., & de Cavalcanti, F. A. C. (2020). Effectiveness of exergames for improving mobility and balance in older adults: A systematic review and meta-analysis. *Systematic Reviews*, *9*, 163. https://doi.org/10.1186/s13643-020-01421-7

Parveen, H., & Noohu, M. M. (2017). Evaluation of psychometric properties of Tinetti performance-oriented mobility assessment scale in subjects with knee osteoarthritis. *Hong Kong Physiotherapy Journal*, *36*, 25–32. https://doi.org/10.1016/j.hkpj.2016.07.001

Pasanen, T., Tolvanen, S., Heinonen, A., & Kujala, U. M. (2017). Exercise therapy for functional capacity in chronic diseases: An overview of meta-analyses of randomised controlled trials. *British Journal of Sports Medicine*, *51*(20), 1459–1465. https://doi.org/10.1136/bjsports-2016-097132

Peng, L., Zeng, Y., Wu, Y., Si, H., & Shen, B. (2022). Virtual reality-based rehabilitation in patients following total knee arthroplasty: A systematic review and meta-analysis of randomized controlled trials. *Chinese Medical Journal*, *135*(2), 153–163. https://doi.org/10.1097/CM9.0000000000001847

Perrochon, A., Borel, B., Istrate, D., Compagnat, M., & Daviet, J.-C. (2019). Exercise-based games interventions at home in individuals with a neurological disease: A systematic review and meta-analysis. *Annals of Physical and Rehabilitation Medicine*, *62*(5), 366–378. https://doi.org/10.1016/j.rehab.2019.04.004

Pirovano, M., Surer, E., Mainetti, R., Lanzi, P. L., & Alberto Borghese, N. (2016). Exergaming and rehabilitation: A methodology for the design of effective and safe therapeutic exergames. *Entertainment Computing*, *14*, 55–65. https://doi.org/10.1016/j.entcom.2015.10.002

Pournajaf, S., Goffredo, M., Pellicciari, L., Piscitelli, D., Criscuolo, S., Le Pera, D., Damiani, C., & Franceschini, M. (2022). Effect of balance training using virtual reality-based serious games in individuals with total knee replacement: A randomized controlled trial. *Annals of Physical and Rehabilitation Medicine*, *65*(6), 101609. https://doi.org/10.1016/j.rehab.2021.101609

Powell, S. M., Larsen, C. A., Phillips, S. M., & Pellegrini, C. A. (2021). Exploring beliefs and preferences for reducing sedentary behavior among adults with symptomatic knee osteoarthritis or knee replacement. *ACR Open Rheumatology*, *3*(1), 55–62. https://doi.org/10.1002/acr2.11216

Prosperini, L., Fortuna, D., Giannì, C., Leonardi, L., Marchetti, M. R., & Pozzilli, C. (2013). Home-based balance training using the Wii balance board: A randomized, crossover pilot study in multiple sclerosis. *Neurorehabilitation and Neural Repair*, *27*(6), 516–525. https://doi.org/10.1177/1545968313478484

Prosperini, L., Tomassini, V., Castelli, L., Tacchino, A., Brichetto, G., Cattaneo, D., & Solaro, C. M. (2021). Exergames for balance dysfunction in neurological disability: A meta-analysis with meta-regression. *Journal of Neurology*, *268*, 3223–3237. https://doi.org/10.1007/s00415-020-09918-w

Pua, Y.-H., Tan, J. W.-M., Poon, C. L.-L., Chew, E. S.-X., Seah, F. J.-T., Thumboo, J., Yeo, S.-J., Woon, E.-L., & Clark, R. A. (2022). Sit-to-stand weight-bearing symmetry performance in total knee arthroplasty: Recovery curves, correlates, and predictive validity with gait speed. *American Journal of Physical Medicine & Rehabilitation*, *101*(7), 666–673. https://doi.org/10.1097/PHM.0000000000001882

R Core Team. (2019). *The R Base Package*. Rdocumentation. https://rdocumentation.org/packages/base/versions/3.6.1

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.r-project.org/

Reis, E., Postolache, G., Teixeira, L., Arriaga, P., Lima, M. L., & Postolache, O. (2019). Exergames for motor rehabilitation in older adults: An umbrella review. *Physical Therapy Reviews*, *24*(3–4), 84–99. https://doi.org/10.1080/10833196.2019.1639012

Reito, A., Järvistö, A., Jämsen, E., Skyttä, E., Remes, V., Huhtala, H., Niemeläinen, M., & Eskelinen, A. (2017). Translation and validation of the 12-item Oxford knee score for use in Finland. *BMC Musculoskeletal Disorders*, *18*, 74. https://doi.org/10.1186/s12891-017-1405-8

Rios, L. P., Ye, C., & Thabane, L. (2010). Association between framing of the research question using the PICOT format and reporting quality of randomized controlled trials. *BMC Medical Research Methodology*, *10*, 11. https://doi.org/10.1186/1471-2288-10-11

Rutkowski, S., Rutkowska, A., Jastrzębski, D., Racheniuk, H., Pawełczyk, W., & Szczegielniak, J. (2019). Effect of virtual reality-based rehabilitation on physical fitness in patients with chronic obstructive pulmonary disease. *Journal of Human Kinetics*, *69*, 149–157. https://doi.org/10.2478/hukin-2019-0022

Rydwik, E., Bergland, A., Forsén, L., & Frändin, K. (2012). Investigation into the reliability and validity of the measurement of elderly people's clinical walking speed: A systematic review. *Physiotherapy Theory and Practice*, *28*(3), 238–256. https://doi.org/10.3109/09593985.2011.601804

Sašek, M., Kozinc, Ž., Löfler, S., Hofer, C., & Šarabon, N. (2021). Objectively measured physical activity, sedentary behavior and functional performance before and after lower limb joint arthroplasty: A systematic review with meta-analysis. *Journal of Clinical Medicine*, *10*(24), 5885. https://doi.org/10.3390/jcm10245885

Sato, K., Kuroki, K., Saiki, S., & Nagatomi, R. (2015). Improving walking, muscle strength, and balance in the elderly with an exergame using kinect: A randomized controlled trial. *Games for Health Journal*, *4*(3), 161–167. https://doi.org/10.1089/g4h.2014.0057

Schünemann, H., Brożek, J., Guyatt, G., & Oxman, A. (Eds.). (2013). *GRADE Handbook*. Cochrane. https://training.cochrane.org/resource/grade-handbook

Segura-Ortí, E., Pérez-Domínguez, B., Ortega-Pérez de Villar, L., Meléndez-Oliva, E., Martínez-Gramage, J., García-Maset, R., & Gil-Gómez, J. A. (2019). Virtual reality exercise intradialysis to improve physical function: A feasibility randomized trial. *Scandinavian Journal of Medicine & Science in Sports*, *29*(1), 89–94. https://doi.org/10.1111/sms.13304

Simek, E. M., McPhate, L., & Haines, T. P. (2012). Adherence to and efficacy of home exercise programs to prevent falls: A systematic review and meta-analysis of the impact of exercise program characteristics. *Preventive Medicine*, *55*(4), 262–275. https://doi.org/10.1016/j.ypmed.2012.07.007

Singh, J. A., Yu, S., Chen, L., & Cleveland, J. D. (2019). Rates of total joint replacement in the United States: Future projections to 2020–2040 using the National Inpatient Sample. *The Journal of Rheumatology*, *46*(9), 1134–1140. https://doi.org/10.3899/jrheum.170990

Skjæret, N., Nawaz, A., Morat, T., Schoene, D., Helbostad, J. L., & Vereijken, B. (2016). Exercise and rehabilitation delivered through exergames in older adults: An integrative review of technologies, safety and efficacy. *International Journal of Medical Informatics*, *85*, 1–16. https://doi.org/10.1016/j.ijmedinf.2015.10.008

Skjæret-Maroni, N., Vonstad, E. K., Ihlen, E. A. F., Tan, X.-C., Helbostad, J. L., & Vereijken, B. (2016). Exergaming in older adults: Movement characteristics while playing stepping games. *Frontiers in Psychology*, *7*, 964. https://doi.org/10.3389/fpsyg.2016.00964

Skou, S. T., Roos, E. M., Laursen, M. B., Rathleff, M. S., Arendt-Nielsen, L., Simonsen, O., & Rasmussen, S. (2015). A randomized, controlled trial of total knee replacement. *New England Journal of Medicine*, *373*(17), 1597–1606. https://doi.org/10.1056/NEJMoa1505467

Stanmore, E. K., Mavroeidi, A., de Jong, L. D., Skelton, D. A., Sutton, C. J., Benedetto, V., Munford, L. A., Meekes, W., Bell, V., & Todd, C. (2019). The effectiveness and cost-effectiveness of strength and balance exergames to reduce falls risk for people aged 55 years and older in UK assisted living facilities: A multi-centre, cluster randomised controlled trial. *BMC Medicine*, *17*, 49. https://doi.org/10.1186/s12916-019-1278-9

Sterne, J. A. C., Savović, J., Page, M. J., Elbers, R. G., Blencowe, N., Boutron, I., Cates, C. J., Cheng, H.-Y., Corbett, M. S., Eldridge, S. M., Hernán, M. A., Hopewell, S., Hróbjartsson, A., Junqueira, D. R., Jüni, P., Kirkham, J. J., Lasserson, T., Li, T., McAleenan, A., … Higgins, J. P. T. (2019). RoB 2: A revised tool for assessing risk of bias in randomised trials. *BMJ*, *366*(l4898). https://doi.org/10.1136/bmj.l4898

Sterne, J. A. C., Sutton, A. J., Ioannidis, J. P. A., Terrin, N., Jones, D. R., Lau, J., Carpenter, J., Rucker, G., Harbord, R. M., Schmid, C. H., Tetzlaff, J., Deeks, J. J., Peters, J., Macaskill, P., Schwarzer, G., Duval, S., Altman, D. G., Moher, D., & Higgins, J. P. T. (2011). Recommendations for examining and interpreting funnel plot asymmetry in meta-analyses of randomised controlled trials. *BMJ*, *343*, d4002. https://doi.org/10.1136/bmj.d4002

Suh, M. J., Kim, B. R., Kim, S. R., Han, E. Y., Nam, K. W., Lee, S. Y., Park, Y. G., & Kim, W. B. (2019). Bilateral quadriceps muscle strength and pain correlate with gait speed and gait endurance early after unilateral total knee arthroplasty: A cross-sectional study. *American Journal of Physical Medicine & Rehabilitation*, *98*(10), 897–905. https://doi.org/10.1097/PHM.0000000000001222

Suleiman-Martos, N., García-Lara, R., Albendín-García, L., Romero-Béjar, J. L., Cañadas-De La Fuente, G. A., Monsalve-Reyes, C., & Gomez-Urquiza, J. L. (2022). Effects of active video games on physical function in independent community-dwelling older adults: A systematic review and meta-analysis. *Journal of Advanced Nursing*, *78*(5), 1228–1244. https://doi.org/10.1111/jan.15138

Taylor, L. M., Kerse, N., Frakking, T., & Maddison, R. (2018). Active video games for improving physical performance measures in older people: A meta-analysis. *Journal of Geriatric Physical Therapy*, *41*(2), 108–123. https://doi.org/10.1519/JPT.0000000000000078

Thong, I. S. K., Jensen, M. P., Miró, J., & Tan, G. (2018). The validity of pain intensity measures: What do the NRS, VAS, VRS, and FPS-R measure? *Scandinavian Journal of Pain*, *18*(1), 99–107. https://doi.org/10.1515/sjpain-2018-0012

Turku University Hospital. (2021). Polven tekonivelleikkaukseen tulevan opas [*Guidebook for knee replacement patients*].

Unver, B., Baris, R. H., Yuksel, E., Cekmece, S., Kalkan, S., & Karatosun, V. (2017). Reliability of 4-meter and 10-meter walk tests after lower extremity surgery. *Disability and Rehabilitation*, *39*(25), 2572–2576. https://doi.org/10.1080/09638288.2016.1236153

Uzor, S., & Baillie, L. (2019). Recov-R: Evaluation of a home-based tailored exergame system to reduce fall risk in seniors. *ACM Transactions on Computer-Human Interaction*, *26*(4), 23. https://doi.org/10.1145/3325280

Valenzuela, T., Okubo, Y., Woodbury, A., Lord, S. R., & Delbaere, K. (2018). Adherence to technology-based exercise programs in older adults: A systematic review. *Journal of Geriatric Physical Therapy*, *41*, 49–61. https://doi.org/10.1519/JPT.0000000000000095

van Buuren, S. (2018). *Flexible imputation of missing data*. CRC press.

van Buuren, S., & Groothuis-Oudshoorn, K. (2011). mice: Multivariate imputation by chained equations in *R*. *Journal of Statistical Software*, *45*(3), 1–67. https://doi.org/10.18637/jss.v045.i03

van der Kooij, K., van Dijsseldonk, R., van Veen, M., Steenbrink, F., de Weerd, C., & Overvliet, K. E. (2019). Gamification as a sustainable source of enjoyment during balance and gait exercises. *Frontiers in Psychology*, *10*, 294. https://doi.org/10.3389/fpsyg.2019.00294

Vandenbroucke, J. P., von Elm, E., Altman, D. G., Gøtzsche, P. C., Mulrow, C. D., Pocock, S. J., Poole, C., Schlesselman, J. J., & Egger, M. (2007). Strengthening the reporting of observational studies in epidemiology (STROBE): Explanation and elaboration. *Annals of Internal Medicine*. https://doi.org/10.7326/0003-4819-147-8-200710160-00010-w1

Vázquez, F. L., Otero, P., García-Casal, J. A., Blanco, V., Torres, Á. J., & Arrojo, M. (2018). Efficacy of video game-based interventions for active aging. A systematic literature review and meta-analysis. *PLOS ONE*, *13*(12), e0208192. https://doi.org/10.1371/journal.pone.0208192

Veritas Health Innovation. (2022). *Covidence systematic review software*. https://www.covidence.org/

Viechtbauer, W. (2010). Conducting meta-analyses in *R* with the metafor package. *Journal of Statistical Software*, *36*(3). https://doi.org/10.18637/jss.v036.i03

Willaert, J., de Vries, A. W., Tavernier, J., Van Dieen, J. H., Jonkers, I., & Verschueren, S. (2020). Does a novel exergame challenge balance and activate muscles more than existing off-the-shelf exergames? *Journal of NeuroEngineering and Rehabilitation*, *17*, 6. https://doi.org/10.1186/s12984-019-0628-3

World Health Organization. (2015). *World report on ageing and health*. http://apps.who.int/iris/bitstream/handle/10665/186463/9789240694811_eng.pdf?sequence=1&isAllowed=y

Wrisley, D. M., & Kumar, N. A. (2010). Functional gait assessment: Concurrent, discriminative, and predictive validity in community-dwelling older adults. *Physical Therapy*, *90*(5), 761–773. https://doi.org/10.2522/ptj.20090069

Yeşilyaprak, S. S., Yıldırım, M. Ş., Tomruk, M., Ertekin, Ö., & Algun, Z. C. (2016). Comparison of the effects of virtual reality-based balance exercises and conventional exercises on balance and fall risk in older adults living in nursing homes in Turkey. *Physiotherapy Theory and Practice*, *32*(3), 191–201. https://doi.org/10.3109/09593985.2015.1138009

Yoon, S., & Son, H. (2020). Effects of full immersion virtual reality training on balance and knee function in total knee replacement patients: A randomized controlled study. *Journal of Mechanics in Medicine and Biology*, *20*(09), 2040007. https://doi.org/10.1142/S0219519420400072

Yoshiko, A., & Watanabe, K. (2021). Impact of home-based squat training with two-depths on lower limb muscle parameters and physical functional tests in older adults. *Scientific Reports*, *11*(1), 6855. https://doi.org/10.1038/s41598-021-86030-7

Zhang, Z.-Y., Tian, L., He, K., Xu, L., Wang, X.-Q., Huang, L., Yi, J., & Liu, Z.-L. (2022). Digital rehabilitation programs improve therapeutic exercise adherence for patients with musculoskeletal conditions: A systematic review with meta-analysis. *Journal of Orthopaedic & Sports Physical Therapy*, *52*(11), 726–739. https://doi.org/10.2519/jospt.2022.11384

APPENDICES

Appendix 1. Literature review

A systematic search of the current literature on employing exergames in the physical rehabilitation of older adults undergoing TKR surgery was conducted in this thesis (Chapter 2.3.4). This appendix includes:

- the search strategy used in one database out of four (TABLE A1),
- the flow diagram of the study selection (FIGURE A1),
- studies excluded in the full text screening (TABLE A2),
- the risk of bias in RCTs included in the literature review (FIGURE A2), and
- the summary of the risk of bias across RCTs included in the literature review (FIGURE A3).

TABLE A1 The search strategy for the Medline (Ovid) database.

#	Searches	Results 8.8.2022
1	Video Games/	6826
2	exergam*.mp.	1077
3	exercise gam*.mp.	77
4	gamifi*.mp.	1366
5	Virtual Reality/ or virtual reality.mp.	15688
6	Virtual Reality Exposure Therapy/	837
7	augmented reality.mp.	3626
8	digital rehabilitation.mp.	31
9	biofeedback.mp. or Biofeedback, Psychology/	11135
10	motion detection.mp.	1643
11	motion-controlled gam*.mp. or motion controller gam*	8
12	1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11	38683
13	total knee replacement.mp. or Arthroplasty, Replacement, Knee/	32210
14	12 and 13	62

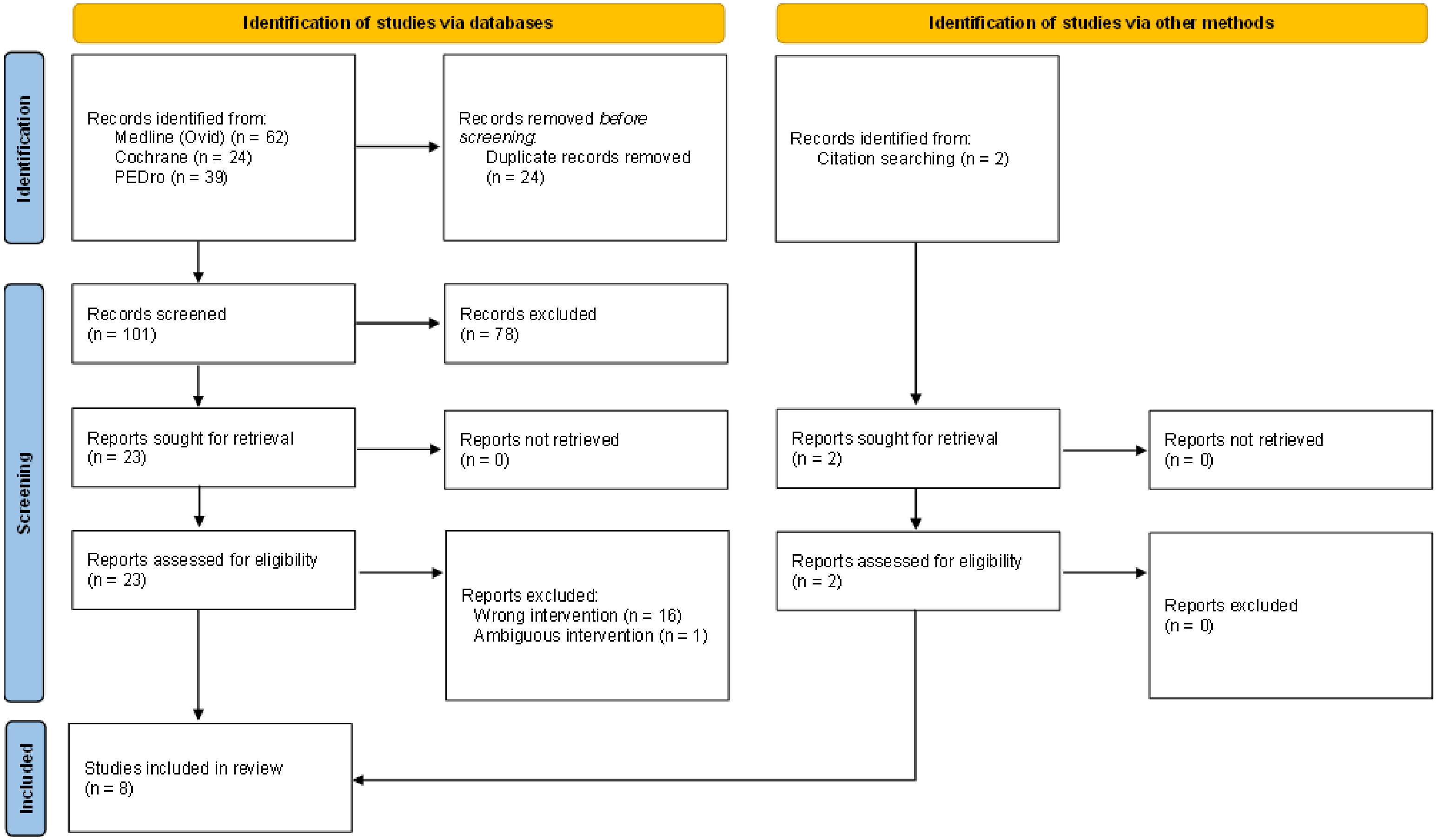

FIGURE A1 Flow diagram of the study selection in the literature review.

Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. https://doi.org/10.1136/bmj.n71

TABLE A2 Studies excluded (n=17) in the literature review.

Reference	Justification
Christensen, J. C., LaStayo, P. C., Marcus, R. L., Stoddard, G. J., Bo Foreman, K., Mizner, R. L., Peters, C. L., & Pelt, C. E. (2018). Visual knee-kinetic biofeedback technique normalizes gait abnormalities during high-demand mobility after total knee arthroplasty. *The Knee*, *25*, 73–82. https://doi.org/10.1016/j.knee.2017.11.010	Wrong intervention
Christensen, J. C., Foreman, K. B., LaStayo, P. C., Marcus, R. L., Pelt, C. E., & Mizner, R. L. (2019). Comparison of 2 forms of Kinetic biofeedback on the immediate correction of knee extensor moment asymmetry following total knee arthroplasty during decline walking. *Journal of Orthopaedic & Sports Physical Therapy*, *49*(2), 105–111. https://doi.org/10.2519/jospt.2019.7800	Wrong intervention
Christensen, J. C., Pelt, C. E., Bo Foreman, K., LaStayo, P. C., Anderson, A. E., Gililland, J. M., & Mizner, R. L. (2021). Longitudinal study of knee load avoidant movement behavior after total knee arthroplasty with recommendations for future retraining interventions. *The Knee*, *30*, 90–99. https://doi.org/10.1016/j.knee.2021.03.014	Wrong intervention
Chughtai, M., Kelly, J. J., Newman, J. M., Sultan, A. A., Khlopas, A., Sodhi, N., Bhave, A., Kolzun II, M. C., & Mont, M. A. (2019). The Role of Virtual Rehabilitation in Total and Unicompartmental Knee Arthroplasty. *Jounal of Knee Surgery*, *32*, 105–110. https://doi.org/10.1055/s-0038-1637018	Wrong intervention
Correia, F. D., Nogueira, A., Magalhães, I., Guimarães, J., Moreira, M., Barradas, I., Teixeira, L., Tulha, J., Seabra, R., Lains, J., & Bento, V. (2018). Home-based rehabilitation with a novel digital biofeedback system versus conventional in-person rehabilitation after total knee replacement: A feasibility study. *Scientific Reports*, *8*, 11299. https://doi.org/10.1038/s41598-018-29668-0	Wrong intervention
Domínguez-Navarro, F., Silvestre-Muñoz, A., Igual-Camacho, C., Díaz-Díaz, B., Torrella, J. V., Rodrigo, J., Payá-Rubio, A., Roig-Casasús, S., & Blasco, J. M. (2021). A randomized controlled trial assessing the effects of preoperative strengthening plus balance training on balance and functional outcome up to 1 year following total knee replacement. *Knee Surgery, Sports Traumatology, Arthroscopy*, *29*(3), 838–848. https://doi.org/10.1007/s00167-020-06029-x	Wrong intervention

(Continues)

TABLE A2 Continued

Reference	Justification
Ficklscherer, A., Stapf, J., Meissner, K. M., Niethammer, T., Lahner, M., Wagenhäuser, M., Müller, P. E., & Pietschmann, M. F. (2016). Testing the feasibility and safety of the Nintendo Wii gaming console in orthopedic rehabilitation: A pilot randomized controlled study. *Archives of Medical Science, 12(6)*,1273–1278. https://doi.org/10.5114/aoms.2016.59722	Wrong intervention
Gianola, S., Stucovitz, E., Castellini, G., Mascali, M., Vanni, F., Tramacere, I., Banfi, G., & Tornese, D. (2020). Effects of early virtual reality-based rehabilitation in patients with total knee arthroplasty: A randomized controlled trial. *Medicine*, *99*(7), e19136. https://doi.org/10.1097/MD.0000000000019136	Ambiguous intervention (not clear if gamified biofeedback)
Koo, K., Park, D. K., Youm, Y. S., Cho, S. D., & Hwang, C. H. (2018). Enhanced reality showing long-lasting analgesia after total knee arthroplasty: Prospective, randomized clinical trial. *Scientific Reports*, *8*, 2343. https://doi.org/10.1038/s41598-018-20260-0	Wrong intervention
Levinger, P., Zeina, D., Teshome, A. K., Skinner, E., Begg, R., & Abbott, J. H. (2016). A real time biofeedback using Kinect and Wii to improve gait for post-total knee replacement rehabilitation: A case study report. *Disability and Rehabilitation: Assistive Technology*, *11*(3), 251–262. https://doi.org/10.3109/17483107.2015.1080767	Wrong intervention
McClelland, J., Zeni, J., Haley, R. M., & Snyder-Mackler, L. (2012). Functional and biomechanical outcomes after using biofeedback for retraining symmetrical movement patterns after total knee arthroplasty: A case report. *Journal of Orthopaedic & Sports Physical Therapy*, *42*(2), 135–144. https://doi.org/10.2519/jospt.2012.3773	Wrong intervention
Piqueras, M., Marco, E., Coll, M., Escalada, F., Ballester, A., Cinca, C., Belmonte, R., & Muniesa, J. (2013). Effectiveness of an interactive virtual telerehabilitation system in patients after total knee arthoplasty: A randomized controlled trial. *Journal of Rehabilitation Medicine*, *45*(4), 392–396. https://doi.org/10.2340/16501977-1119	Wrong intervention
Prvu Bettger, J., Green, C. L., Holmes, D. N., Chokshi, A., Mather, R. C., Hoch, B. T., de Leon, A. J., Aluisio, F., Seyler, T. M., Del Gaizo, D. J., Chiavetta, J., Webb, L., Miller, V., Smith, J. M., & Peterson, E. D. (2020). Effects of virtual exercise rehabilitation in-home therapy compared with traditional care after total knee arthroplasty: VERITAS, a randomized controlled trial. *Journal of Bone and Joint Surgery*, *102*(2), 101–109. https://doi.org/10.2106/JBJS.19.00695	Wrong intervention

(Continues)

TABLE A2 Continued

Reference	Justification
Villafañe, J. H., Isgrò, M., Borsatti, M., Berjano, P., Pirali, C., & Negrini, S. (2017). Effects of action observation treatment in recovery after total knee replacement: A prospective clinical trial. *Clinical Rehabilitation*, *31*(3), 361–368. https://doi.org/10.1177/0269215516642605	Wrong intervention
Wang, T.-J., Chang, C.-F., Lou, M.-F., Ao, M.-K., Liu, C.-C., Liang, S.-Y., Wu, S.-F. V., & Tung, H.-H. (2015). Biofeedback relaxation for pain associated with continuous passive motion in Taiwanese patients after total knee arthroplasty. *Research in Nursing & Health*, *38*, 39–50. https://doi.org/10.1002/nur.21633	Wrong intervention
Wilk-Frańczuk, M., Zemła, J., & Śliwiński, Z. (2010). The application of biofeedback exercises in patients following arthroplasty of the knee with the use of total endoprosthesis. *Medical Science Monitor*, *16*(9), CR423-CR426. https://medscimonit.com/abstract/index/idArt/881129	Wrong intervention
Zeni, J., Abujaber, S., Flowers, P., Pozzi, F., & Snyder-Mackler, L. (2013). Biofeedback to promote movement symmetry after total knee arthroplasty: A feasibility study. *Journal of Orthopaedic & Sports Physical Therapy*, *43*(10), 715–726. https://doi.org/10.2519/jospt.2013.4657	Wrong intervention

Study ID	Experimental	Comparator	Outcome	D1	D2	D3	D4	D5	Overall
Christiansen et al. 2015	SP & EG	SP	physical function	+	+	+	+	+	+
Fung et al. 2012	SP & EG	SP & AE	physical function and pain	+	+	+	!	!	!
Hadamus et al. 2021	SP & EG	SP	physical function	!	!	+	+	!	!
Hardt et al. 2018	SP & EG	SP	physical function and pain	+	-	-	!	!	-
Jin et al. 2018	SP & EG	SP	physical function and pain	!	!	+	!	!	!
Pournajaf et al. 2022	SP & EG	SP	physical function and pain	+	+	+	!	+	!
Yoon & Son 2020	SP & EG	SP & AE	physical function	+	!	-	!	!	-

+ Low risk
! Some concerns
- High risk

FIGURE A2 Risk of bias in randomized controlled trials (n=7) included in the literature review.
SP = standard protocol, EG = exergaming, AE = additional exercising
D1 = Randomization process, D2 = Deviations from the intended interventions, D3 = Missing outcome data, D4 = Measurement of the outcome, D5 = Selection of the reported results

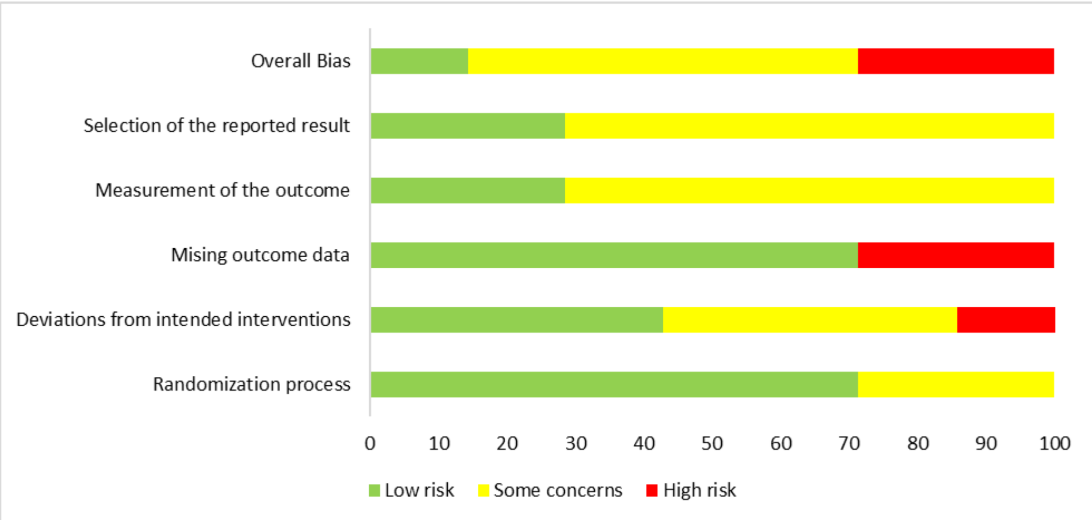

FIGURE A3 Summary of the risk of bias across randomized controlled trials (n=7) included in the literature review.

ORIGINAL PAPERS

I

MOVEMENT CHARACTERISTICS DURING CUSTOMIZED EXERGAMES AFTER TOTAL KNEE REPLACEMENT IN OLDER ADULTS

by

Maarit Janhunen, Antti Löppönen, Simon Walker, Taavi Punsár, Niina Katajapuu, Sulin Cheng, Juha Paloneva, Konsta Pamilo, Mika Luimula, Raija Korpelainen, Timo Jämsä, Ari Heinonen & Eeva Aartolahti, 2022

Frontiers in Sports and Active Living 4 (915210), 1–12

https://doi.org/10.3389/fspor.2022.915210 frontiers | Frontiers in Sports and Active Living

TYPE Original Research
PUBLISHED 27 July 2022
DOI 10.3389/fspor.2022.915210

Check for updates

OPEN ACCESS

EDITED BY
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SPECIALTY SECTION
This article was submitted to Biomechanics and Control of Human Movement,
a section of the journal Frontiers in Sports and Active Living

RECEIVED 07 April 2022
ACCEPTED 30 June 2022
PUBLISHED 27 July 2022

CITATION
Janhunen M, Löppönen A, Walker S, Punsár T, Katajapuu N, Cheng S, Paloneva J, Pamilo K, Luimula M, Korpelainen R, Jämsä T, Heinonen A and Aartolahti E (2022) Movement characteristics during customized exergames after total knee replacement in older adults.
Front. Sports Act. Living 4:915210.
doi: 10.3389/fspor.2022.915210

Movement characteristics during customized exergames after total knee replacement in older adults

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Introduction: There is limited understanding of how older adults can reach kinematic goals in rehabilitation while performing exergames and conventional exercises, and how similar or different the kinematics during exergaming are when compared with conventional therapeutic exercise with similar movement. The aim of this study was to describe the movement characteristics performed during exercise in custom-designed exergames and conventional therapeutic exercises among patients who have undergone unilateral total knee replacement (TKR). In addition, the secondary aim was to assess the relation of these exercise methods, and to assess participants' perceived exertion and knee pain during exergaming and exercising.

Materials and methods: Patients up to 4 months after the TKR surgery were invited in a single-visit exercise laboratory session. A 2D motion analysis and force plates were employed to evaluate movement characteristics as the volume, range, and intensity of movement performed during custom-designed knee extension-flexion and weight shifting exergames and conventional therapeutic exercises post TKR. The perceived exertion and knee pain were assessed using the Borg Rating of Perceived Exertion and Visual Analog Scale, respectively.

Results: Evaluation of seven patients with TKR [age median (IQR), 65 (10) years] revealed that the volume and intensity of movement were mostly higher during exergames. Individual goniometer-measured knee range of motion were achieved either with exergames and conventional therapeutic exercises, especially in knee extension exercises. The perceived exertion and knee pain were similar after exergames and conventional therapeutic exercises.

Conclusions: During custom-designed exergaming the patients with TKR achieve the movement characteristics appropriate for post-TKR rehabilitation without increasing the stress and pain experienced even though the movement characteristics might be partly different from conventional therapeutic exercises by the volume and intensity of movement. Physical therapists could consider implementing such exergames in rehabilitation practice for patients with TKR once effectiveness have been approved and they are widely available.

KEYWORDS

video games, exercise therapy, kinematics, musculoskeletal system, physical therapy, rehabilitation

Introduction

Total knee replacement (TKR) is a surgical treatment aiming to reduce pain and to restore knee joint function in severe osteoarthritis common seen among older adults (Bruyère et al., 2019). Therapeutic exercise managed by the physical therapist typically begins on the day of the surgery and is intended to reduce swelling and to increase muscle strength, mobility, balance and movement symmetry and the range of motion (ROM) in the operated knee (Jette et al., 2020). Enhanced therapeutic exercise after discharge from the hospital is essential to improve functional performance (Papalia et al., 2020).

An alternative method to conventional therapeutic exercise for patients with TKR is gamified exercising (Wang et al., 2019), also referred to as active video gaming or exergaming (Oh and Yang, 2010). While exergaming, the technology follows the player's reactions and movements, such as the extension and flexion of the knee, which affect the course and outcomes of the exergame. With this motion tracking technique, exergames can be tailored to a desired exercise movement, such as knee extension movement (Pirovano et al., 2016). Both commercially available and custom-designed exergames have been used in physical rehabilitation in older adults (Skjæret et al., 2016). Studies, which have evaluated the realization of movement during exergaming have shown that similar exergames (Skjæret-Maroni et al., 2016; de Vries et al., 2018) or different levels of difficulty in a single exergame (Skjæret-Maroni et al., 2016) may lead to significantly different movements, and movements trained in the exergames may poorly meet all targeted aspects of the specific rehabilitation goal (Tahmosybayat et al., 2018).

However, there is limited understanding of kinematics during exergaming and how exergaming relates to conventional therapeutic exercises. Because of this lack of knowledge, there are limited possibilities to design specific and progressive exergame-based therapeutic exercises more broadly in rehabilitation (Pirovano et al., 2016). Further, this knowledge will determine whether appropriate exergames can be used in intervention studies evaluating the effectiveness of exergaming. Therefore, the objective of this study was to investigate the movement characteristics that patients with TKR performed during custom-designed exergames developed for postoperative rehabilitation. The following research questions were addressed: (1) What movement characteristics patients with TKR achieve while exergaming? (2) Do movement characteristics of custom-designed exergames relate with movement characteristics of conventional therapeutic exercises in patients with TKR?

Materials and methods

Study design

This study employed 2D motion analysis and force plates to evaluate movement characteristics performed during custom-designed knee extension-flexion and weight shifting exergames and conventional therapeutic exercises post TKR. Participants up to 4 months after the TKR surgery ($n = 7$) performed conventional therapeutic exercises and exergames sequentially on a single-visit exercise laboratory session. The outcomes were the volume, range and intensity of movement, and perceived exertion and knee pain during exercising. This pilot study is part of the "Business Ecosystems in Effective Exergaming" project (BEE) and "Gamification in Knee Replacement Rehabilitation" randomized controlled trial (BEE-RCT, ClinicalTrials.gov Identifier: NCT03717727)

TABLE 1 Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Interested in participating in the study.	Revision or complications related to the TKR surgery.
Live in the region of the city of Jyväskylä.	Chest pain during exercise or other physical exertion.
60–75 years of age.	Unreasonable shortness of breath.
Primary unilateral TKR*	Seizures of unconsciousness, fainting or dizziness.
Mechanical axis of the limb in varus.	Heart medication.
Normal vision with or without eyeglasses.	
No rheumatoid arthritis or other inflammatory joint disease.	
No fracture or other biomechanical disruptions that has affected the lower limb within 1 year before surgery.	
No diagnosed memory disorder.	

*Surgical decision made or <3 months after surgery.

(Aartolahti et al., 2022). This study was approved by the Ethics Committee of the Central Finland Health Care District (register number 4U/2018) and had hospital research permission from the Central Finland Central Hospital. Prior to participation in the study, eligible patients gave their written informed consent.

Participants

Patients undergoing TKR were recruited during the hospital pre- or postoperative outpatient visit. The inclusion and exclusion criteria are presented in Table 1.

Procedure

Participants attended one 2-hour test session held in the exercise laboratory of the University of Jyväskylä before 4 months had elapsed since their TKR. At the beginning of the test session, participants completed a Western Ontario and McMaster Universities Osteoarthritis index (WOMAC) (McConnell et al., 2001) questionnaire to assess pain (score 0–20), stiffness (score 0–8) and physical function (score 0–68) during the previous 7 days and a visual analog scale (VAS) (Jensen et al., 2003; Thong et al., 2018) to assess knee pain (score 0–100) during the past 24 h. After completing the WOMAC and VAS, the knee joint ROM of the operated knee was measured using a goniometer (Gogia et al., 1987) while the participant was in a supine position. Thereafter, participants performed exercise protocols; first, participants performed conventional post-TKR exercises, and second, custom-designed exergames were performed immediately after those exercises (Table 2).

Conventional therapeutic exercises

The conventional post-TKR exercises (later referred to as conventional exercises) included 10 exercise following instructions of South West Finland Health Care District (South West Finland Health Care District, 2015). Exercises aimed to increase blood circulation, muscle strength and knee ROM of the operated lower limb. Participants were instructed to perform 10 repetitions in each conventional exercise at their own pace. This meant that the duration of each exercise varied both individually and between participants, as the participants could choose to perform repetitions at different paces. For example, knee flexion exercise sitting at a slow pace and standing at a faster pace.

Custom-designed exergames

Ten custom-designed exergames (Futuristic Interactive Technologies research group, Turku GameLab, Turku University of Applied Sciences, Finland) used in this study were developed using a Unity game engine (Unity Technologies, USA). The development was made in various test-generate cycles following user-centric design principles and Hevner's IS Research Framework (Hevner et al., 2004). The hardware used was a Kinect 2 motion sensor (Microsoft, USA) and a laptop computer (Micro-Star International, Taiwan) connected to a flat screen television (43 inches). Each exergame included a storyline, which explained the goal of the game, and participants' body movements acted as a game controller. These movements tracked by the Kinect sensor were transferred on the screen to move the avatar. Four exergames (the Cave Game, Rowing Game, Intruders and Squat Pong) included a pre-calibration that scaled the maximum ROM of the participant's operated knee prior to exergaming so that exercising occurred according to the participant's current mobility limitations. Game duration was based on maximum repetitions (the Cave Game), maximum time (the Pick Up, Bubble Runner, Hat Trick, Brick Breaker, Hiking and Toy Golf) or a combination of maximum repetitions and time (the Intruders, Rowing Game and Squat Pong). The combination of repetitions and time means that the game could end after the maximum number of repetitions specified for game, but no later than after the maximum time specified for game. Participants were instructed to perform repetitions according to games' storylines for their duration.

Knee extension-flexion exercises and exergames were performed only with the operated lower limb. Participants were allowed to have breaks between conventional exercises and exergames. Participants took support from the back of the chair when they had to stand on one leg during the performance (the Flexion standing and Rowing Game). More detailed information

TABLE 2 Exercise protocols used in the study: (1) conventional therapeutic exercises and (2) custom-designed exergames.

Exercise	Exercise position	Exercise description	Movement during exercise	Primary knee movement
Conventional therapeutic exercises				
Ankle pumps*	SU	Bending and straightening of ankles	Flex and extend	NA
Extension supine I*	SU	Pressing the back of the operated knee against the treatment table for 5 s while ankles are flexed	Flex and extend	Ext
Flexion supine*	SU	Bending the operated knee by sliding the foot along the treatment table	Flex and extend	Flx
Extension supine II*	SU	Straightening the operated knee and maintaining the muscle tension for a few seconds while ankle is flexed and back of the operated knee is on half round bolster	Flex and extend	Ext
Extension supine III*	SU	Lifting the straightened operated lower limb up from the treatment table and maintaining the muscle tension for a few seconds while the ankle is flexed	Flex and extend	Ext
Flexion sitting†	SI	Bending the operated knee as much as possible (foot may be slide along the floor)	Flex and extend	Flx
Extension sitting†	SI	Straightening the operated knee and maintaining the muscle tension for a few seconds while ankle is flexed	Flex and extend	Ext
Extension standing I	ST	Raising heels until standing on toes	Flex and extend	Ext
Extension standing II	ST	Taking a step forward with the operated lower leg, straightening the knee and transferring the weight on the leg	Weight transfer	Ext
Flexion standing†	ST	Bending the operated knee and maintaining the muscle tension while keeping thighs next to each other	Flex and extend	Flx
Custom-designed exergames				
Knee extension-flexion exergames				
Rowing Game†	ST	Bending the operated knee to row a boat	Flex and extend	Flx
Cave Game†	SI	Straightening and bending the operated knee to catch flies	Flex and extend	Ext
Intruders†	SI	Straightening and bending the operated knee to shoot zombies	Flex and extend	Ext
Squatting exergames				
Squat Pong†	ST	Squatting and raising heels until standing on toes to hit the ball with a tennis racket	Squat	Flx
Pick Up†	ST	Squatting to pick up vegetables	Squat	Flx
Weight shifting exergames				
Bubble Runner‡	ST	Transferring the weight laterally from foot to another to blow up balloons on the road	Weight transfer	Ext
Hat Trick‡	ST	Transferring the weight laterally from foot to another to throw objects to a sombrero	Weight transfer	Ext
Piloting exergames				
Brick Breaker	SI	Move lower limb laterally to catch falling objects	Hip Abd/Add	NA
Toy Golf	ST	Balance, golf swing, and squatting to give boost to a golf ball	Balance control	Flx
Hiking	ST	Marching to move forward on a trail	Marching	Flx

SU, Supine in the treatment table; SI, Sitting in the chair; ST, Standing; NA, Not Applicable; Ext, Extension; Flx, Flexion; Abd/Add, Abduction/ Adduction.
*Acted as warm-up exercises.
†Included in motion analysis.
‡Included in force plate analysis.
Conventional exercises and exergames are presented in the order in which participants performed them during a test session.

of conventional exercises and exergames are presented in the protocol of the BEE-RCT (Aartolahti et al., 2022).

Measurements

Movement characteristics

Instrumentation

Video data to evaluate knee 2D-kinematics from the sagittal plane during exercising were recorded with a Sony RX-10 III camera (Sony Corporation, Japan) (Norris and Olson, 2011; Schurr et al., 2017). Video recording was continuous throughout the performance of three conventional exercises (the Flexion sitting, Extension sitting and Flexion standing) and exergames (Table 2). Passive markers for 2D motion analysis were placed at participants' joint axes of shoulder (greater tubercle of the humerus), hip (greater trochanter of femur), knee (lateral epicondyle of femur) and ankle (lateral malleolus of fibula). Around these points, the knee and hip joint angles were determined. A camera was placed on a tripod seven meters from the participant so that the camera was facing the participant's lateral side of the body while he or she was standing on force plates. The knee extension-flexion exergames and the conventional exercise were recorded from the operated side and the squatting exergames from the left side. The optical axis of the camera was positioned at the height of the participant's pelvis. At the beginning of each test session, calibration was performed by using a rectangular calibration frame (200.0 × 110.8 cm). The camera's frame rate was 50 frames per second (50 Hz) and the shutter speed was 1/1,250 s.

A force measure to represent how evenly the participants stood still and how much participants leaned on the operated lower limb during exergaming was captured using Vicon Nexus 2 (version 2.7 & 2.8) software (Vicon Motion Systems Ltd, UK), while the participant stood with one foot on each of the two AMTI MiniAMP MSA-6 force plates (Advanced Mechanical Technology Inc., USA). Force plate data were gathered throughout the performance of weight shifting exergames (Bubble Runner and Hat Trick). Participants were instructed to keep their feet throughout the exergames on force plates, which had fixed placement in the exercise laboratory.

Data processing

The motion analysis data was filtered with a 15 Hz Butterworth 4th- order-zero-lag low-pass filter (Schreven et al., 2015). Videos were converted to AVI format with Kinovea 0.8.15 software (Kinovea, 2021), and a sagittal 2D model was created in Vicon Motus 10.0.1 motion analysis software (Vicon Motion Systems Ltd, UK) (Norris and Olson, 2011). Piloting exergames (the Brick Breaker, Toy Golf and Hiking) were performed for future development purposes, but kinematics were not assessed in the present study. Two participants are missing one exergame motion analysis data due to wrong performance (Participant 1: Intruders) and software (Participant 2: Pick Up) issues encountered during exergaming (Supplementary material).

Movement characteristics were identified by a custom-made MATLAB script (R2019a, The MathWorks Inc., Natick, Massachusetts, USA). For the analysis, the active time of exercising was defined as duration from which the passive time, i.e., the time the participant got ready to start the conventional exercise or waited for the exergame to start, was removed.

To standardize the analysis, the limits to identifying a single repetition were determined. By these limits, the calculation algorithm detects only full repetitions and not a small movement near the rest position. First, a knee angle limit was determined for each test subject based on participants' individual active knee ROM measured with a goniometer. All movements across this limit were considered active movements. After that, for knee extension and flexion exergames (the Rowing Game, Cave Game and Intruders) and conventional exercises, the limit was defined as half individuals' active knee ROM, and for squatting exergames (the Squat Pong and Pick Up) as a quarter of individuals' active knee ROM. Finally, MATLAB's "findpeaks" function was used to define the repetitions and their knee joint ROM from the active movement. For the "findpeaks" function arguments, it was determined that the time between repetitions was set to 0.7 s in the exergames and 2.2 s in the conventional exercises. The minimum peak prominence, which defines the accepted variation between repetitions, was set to 20 degrees.

The *volume of movement* was analyzed by all repetitions completed during the session, repetition rate (repetitions per minute) and duration as the total duration of the gaming or exercising session. In addition, to identify repetitions that reached the active knee ROM (% in active ROM) measured with a goniometer, the angle range, so-called target area, was defined for each test subject. This was set by adding ten degrees to the active knee ROM, which can be considered an error in goniometer measurement (Lenssen et al., 2007) and motion analysis (Elliott et al., 2007). The *range of movement* during the gaming or exercising session was analyzed by knee joint ROM during extension and flexion movement. The *intensity of the movement* was determined using knee angular velocity which was defined as the average angular velocity per second during active movement, and the using knee angle accumulation which was defined as the total angular movement per minute during the entire exercise. An example of repetition identification is presented in Figure 1 and graphs of the analysis are provided in the Supplementary material.

Force plate data was collected at a frequency of 30 Hz and was filtered with a 10 Hz Butterworth 4th- order-zero-lag low-pass filter. The *resultant force* during exergaming on the operated lower limb in relation to the exergame duration was calculated from the two force plate data, which was classified every 10% so that 100% represents the situation where participants were fully leaning on the operated lower limb, and these values are

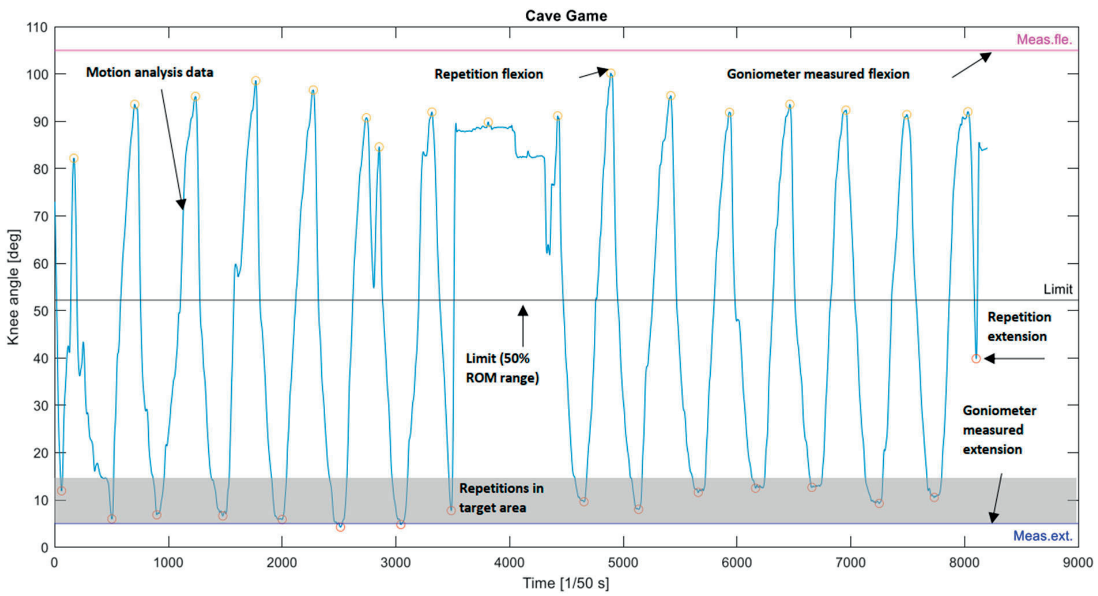

FIGURE 1
Identification of repetitions from the motion analysis data of the knee extension-flexion exergame (the Cave Game) where knee extension was the primary movement goal.

presented as the mean and standard deviation (SD). In addition, the average *resultant force* on the operated and non-operated lower limbs as a percentage was calculated while participants stood still.

Knee pain and perceived exertion in exercises

Subjective perceived exertion and knee pain during exercising were assessed using the Borg Rating of Perceived Exertion (Borg, 1982) and VAS, respectively. The assessment took place after performance of the conventional exercises, the knee extension-flexion exergames (the Rowing Game, Gave Game and Intruders), the squatting exergames (the Squat Pong and Pick Up), and the weight shifting (the Bubble Runner and Hat Trick) and piloting exergames (the Brick Breaker, Toy Golf and Hiking).

Statistical analysis

All statistical analyses were performed in R version 4.0.3 (R Core Team, 2020). The results of the volume and range of movement are reported as the median and interquartile range (IQR), except for repetitions in the target area, which are reported as the mean and SD. The results of the intensity of movement are reported as the mean and SD. The differences in the range and intensity of movement between the conventional exercises and exergames were analyzed using the Wilcoxon signed rank test with the level of significance set at 0.05.

Results

Eleven individuals were interested in participating in the study. Four patients were excluded because of shortness of breath and dizziness ($n = 1$), change in interest for participation ($n = 2$) and abnormal mechanical axis of the limb (valgus) ($n = 1$). The characteristics of the seven individuals included to participate in the study are presented in Table 3. Participants had a low level of symptoms, good physical function, and mild knee pain during the previous day. None of the participants obtained full knee extension (0°), and only one reached the degree of knee flexion (110°), which is the proposed degree of performing normal daily activities (Rowe et al., 2000).

Movement characteristics

Volume

The repetition rate was similar between the exergames (14–15 repetitions/minute) and the conventional exercises (13–15 repetitions/minute), with the exception of the performed repetitions in the Rowing Game (34 repetitions/minute) and the Cave Game (eight repetitions/minute) (Table 4). Variation was observed in the proportions of the repetitions that

TABLE 3 Participant characteristics ($n = 7$).

	Value
Age (years)	65 (10)
Sex (male/female) (n)	1 / 6
Time from TKR (months)	3.5 (2.75)
WOMAC*	
Pain (0–20)	5 (5)
Stiffness (0–8)	2 (1)
Physical function (0–68)†	15 (24)
Total (0–96)	21 (28)
Pain in previous 24 h (VAS 0–100)‡	42 (45)
Active ROM of operated knee (goniometer)§	
Knee extension	12 (7)
Knee flexion	100 (18)
Resultant force (%) on operated lower limb|	48 (2)

IQR, interquartile range; TKR, Total Knee Replacement; WOMAC, Western Ontario and McMaster Universities Osteoarthritis index; VAS, Visual Analog Scale; ROM, Range of Motion.
*Higher score indicates worse pain, stiffness, and functional limitations.
†For one participant who ticked two options in two questions, values that indicated more severe condition was selected.
‡Higher score indicates worse pain.
§Active range of motion in degrees measured in the supine position; Zero degrees (0°) of the knee joint is a position where the knee is fully extended.
|$n = 6$.
The value is the median (IQR) unless otherwise stated.

reached goniometer measured active knee ROM in exergames and conventional exercises. Only in the knee extension performed with conventional exercise (the Extension sitting) each repetition reached measured knee ROM (Table 4).

Range

Participants extended the knee similarly in the Intruders and conventional Extension sitting exercise (both 11°, $p > 0.05$), but significantly less in the Cave Game than in the conventional Extension sitting exercise (14° and 11°, respectively, $p = 0.018$) (Tables 4, 5). Significantly higher knee flexion ROM in the Rowing Game was seen when it was compared to the conventional Flexion standing exercise (93° and 89°, respectively, $p = 0.018$) (Tables 4, 5). The knee flexion ROM in the conventional exercises (89° and 94°) was significantly larger than that in the Squatting exergames, i.e., the Squat Pong (56°, $p = 0.018$) and Pick Up (70°, $p < 0.05$) games (Tables 4, 5).

Intensity: Angular velocity

In the knee extension exergames, the Intruders game was significantly more intense than the conventional Extension sitting exercise (74.4 and 35.5°/s, respectively, $p = 0.046$) (Tables 4, 5). Significantly higher intensity in the Rowing Game was apparent when compared to the conventional Flexion sitting exercise (67.6 and 20.9°/s, respectively, $p = 0.018$) (Tables 4, 5). Movement in the conventional Flexion standing exercise (36.9°/s) was significantly more intense ($p < 0.05$) than in the Squatting exergames (the Squat Pong and Pick Up) (20.1 and 28.1°/s, respectively) (Tables 4, 5).

Intensity: Resultant force

Visual inspection of movement during the weight shifting exergames (the Bubble Runner and Hat Trick) suggests that the majority of the resultant force was produced by the non-operated lower limb (Figure 2).

Knee pain and perceived exertion in exercises

Participants experienced mild knee pain after performing conventional exercise (median: 8; IQR: 6), knee extension-flexion exergames (15; 12), squatting exergames (7; 17), and weight shifting and piloting exergames (4; 4). The perceived exertion was "very light" after the weight shifting and piloting exergames (10; 4), "light" after the conventional exercises (12; 5) and the knee extension-flexion exergames (11; 3), and "somewhat hard" after the squatting exergames (13; 4).

Discussion

The study demonstrated some of the expected results regarding individual and intergame variation during exergaming, which has also been observed in other studies (Skjæret-Maroni et al., 2016; de Vries et al., 2018). The present study observed a higher number of repetitions performed in the exergames, which was due to longer exercise duration. When repetitions were proportional to duration of exercise, repetition rate was more equivalent between exergames and conventional exercises. Moreover, when exergames were designed to follow more closely the movement of the conventional exercise, the measured movement characteristics were indeed mainly similar. Smaller knee ROM during squatting exergames, in turn, may be a result of the simultaneous function of multiple joints and muscle groups of the lower body required during squatting and thus is a more holistic exercise than isolated knee extension or flexion exercise. Nevertheless, the movement characteristics of exergames with squatting actions are worth studying and can be considered a good addition to the postoperative rehabilitation of patients with TKR (Zeni et al., 2013; Tsuzuku et al., 2018), which is also supported by the results of low perceived exertion and knee pain during the squatting exergames.

When clinically evaluating the study results of the knee ROM during the knee extension-flexion exergames, 80–96% of repetitions performed during exergaming reached

TABLE 4 Movement characteristics demonstrated by the patients with TKR ($n = 7$) in measured exercises whose movement goal was knee extension and flexion.

	Volume				Range		Intensity	
	Duration	Repetitions			Knee joint ROM (°)		Angular velocity	Angle accumulation
	(seconds) Med (IQR)	Total (no) Med (IQR)	Rate (reps/min) Med (IQR)	(% in active ROM) Mean (SD)	Extension Med (IQR)	Flexion Med (IQR)	(°/s) Mean (SD)	(°/min) Mean (SD)
Knee extension-flexion exergames (incl. squatting games)								
Cave game	177 (21)	24 (10)	8 (2)	80 (14)	14 (5)	81 (14)	25.1 (11.0)	1,297.8 (469.4)
Intruders*	70 (85)	19 (7)	15 (8)	96 (3)	11 (5)	95 (20)	74.4 (36.6)	2,769.7 (2,094.5)
Rowing game	62 (8)	31 (14)	34 (11)	83 (37)	19 (9)	93 (11)	67.6 (29.8)	5,021.2 (1,976.8)
Squat pong	118 (32)	28 (8)	14 (3)	0 (0)	11 (6)	56 (14)	20.1 (9.7)	1,249.5 (606.7)
Pick up*	93 (4)	21 (3)	14 (1)	14 (33)	8 (9)	70 (14)	28.1 (8.9)	1,666.6 (560.5)
Conventional exercises								
Extension sitting	36 (15)	10 (1)	15 (6)	100 (0)	11 (5)	79 (13)	35.5 (20.4)	1,973.2 (878.7)
Flexion sitting	42 (20)	9 (3)	13 (5)	97 (8)	62 (11)	94 (13)	20.9 (6.6)	1,071.3 (403.2)
Flexion standing	40 (7)	10 (0)	15 (3)	61 (44)	17 (3)	89 (14)	36.9 (9.6)	2,083.0 (441.7)

Med, median; IQR, interquartile range; SD, standard deviation; Repetitions; Rate (reps/min), time-proportional rate of repetitions; ROM, range of motion; Repetitions; (% in active ROM), repetitions that reached the ROM measured with a goniometer (presented from the primary knee movement of the exergame/conventional exercise).

°Degree.

*$n = 6$.

Exercises are presented in the order of the exercise protocols (exergames and conventional exercise) and the primary knee movement in the exercise (extension and flexion).

TABLE 5 Significance levels (*p*-values) for differences in the range and intensity of movement in the exergames and conventional exercises according to the primary movement goal: (A) knee extension and (B) knee flexion.

(A)		Cave Game		Intruders			
	N	ROM	Velocity	ROM	Velocity		
Extension sitting	7	0.018*	0.176	0.345	0.046*		
(B)		**Rowing Game**		**Squat Pong**		**Pick Up**	
	N	**ROM**	**Velocity**	**ROM**	**Velocity**	**ROM**	**Velocity**
Flexion sitting	7	0.237	0.018*	0.018*	0.735	0.028*	0.173
Flexion standing	7	0.018*	0.063	0.018*	0.018*	0.046*	0.046*

ROM, Knee joint range of motion; Velocity, Angular velocity.
*Wilcoxon signed rank test p < 0.05.

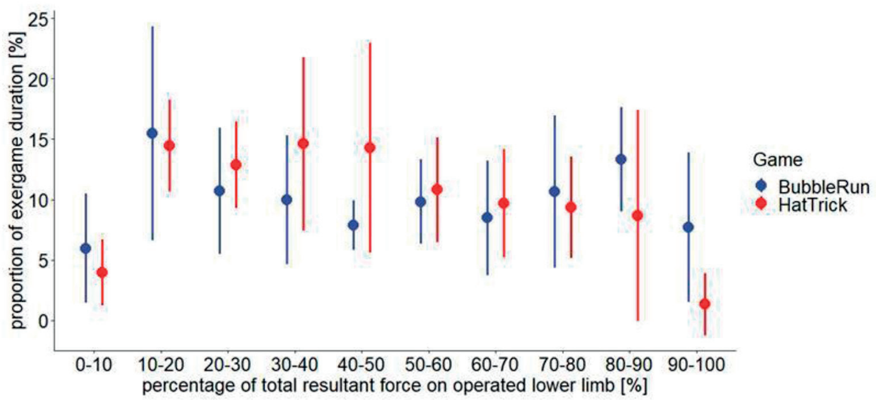

FIGURE 2
The resultant force (the mean and SD) produced by the operated lower limb (*n* = 7) during weight shifting exergames (the Bubble Runner and Hat Trick).

the target area calculated from the goniometer-measured knee ROM. Participants even extended the knee over the goniometer-measured extension in the Intruders game but did not achieve goniometer-measured flexion in the Rowing Game. However, repetitions in the target area and knee flexion degree were larger in the Rowing Game than in the conventional knee flexion exercise with the same movement. These outcomes are positive indicators of successful implementation of conventional exercise as a game (Pirovano et al., 2016), although it is unknown whether the observed significance levels in ROM during exercise actually translates to meaningful clinical difference, and moreover, the repetitions made during exergames and conventional exercises may not be realized fully similarly. For example, due to exergame's storyline, there may be a longer time between repetitions, while it may be fairly constant in conventional exercise. This was seen especially in the motion analysis data of Intruders and Extension sitting exercise.

When evaluating the movement characteristics demonstrated during exergaming, some personal and gaming-related issues that may have an impact on the achievement of exercising goals and adherence should be considered. The player's intentional or unconscious choices during exergaming may negatively affect the number or quality of movements made. This finding has been observed as a learning effect among healthy older adults (Skjæret-Maroni et al., 2016; de Vries et al., 2018), but in patients with TKR, it may also be related to persistent postoperative pain (Beswick et al., 2012) or asymmetry in placing weight on the operated lower limb (Christiansen et al., 2013). For example, despite the exergame's story outline, patients with TKR could choose to predominately lean on to their non-operated lower limb for a longer time, not to perform the repetition, or not to squat to the desired knee flexion angle. Hence, further study into user experiences may provide a benefit for developing more immersive exergames (Dulau et al., 2019).

However, it should be noted that participants included in the current study had low pain during exergaming, and clinical asymmetry between operated and non-operated lower limbs was low while standing still. Consequently, the exergames examined in the present study appear to be suitable and safe to perform for the studied population, and some individuals may even find gaming more fun and a motivating form of exercise (Pyae et al., 2017). It is also worth noting that the incidence of TKRs among younger age groups is increasing, and these patients may be potentially more interested in using exergames in rehabilitation (National Institute for Health Welfare, 2021). In addition, the exergames used in the study were designed so that participants performed both knee extension and flexion movements in one exercise and thus replaced two conventional exercises. These aspects could increase adherence to exercising when the goals of the two exercises may be achieved in one exercise, leading to a shorter duration of exercising sessions reportedly preferred by older adults (Zadro et al., 2019).

To the best of our knowledge, this was the first study specifically to investigate kinematics, perceived exertion, and knee pain during custom-designed exergames and their relation to conventional postoperative exercises after TKR. This type of research is necessary when designing exergames or future randomized, controlled trials investigating the effectiveness of exergames for rehabilitation with specific exercise goals. This knowledge may also lead to the development of better and more customized exergames, the use of which in effectiveness studies is still low (Corregidor-Sánchez et al., 2021). Moreover, in the future, when exergames are developed further, physiological measurements, such as muscle activation, heart rate and blood pressure, could be studied to gain an even better understanding of physical loading during exergaming (da Cruz et al., 2020; Willaert et al., 2020). Finally, game developers may consider how exercise instructions may be added or merged to exergames (Pirovano et al., 2016) and provide, for example, the possibility for study participants or persons in the rehabilitation process to use exergames without supervision.

The strengths of this study were valid and appropriate instrumentation, such as custom-designed exergames developed for patients with TKR and 2D motion analysis (Norris and Olson, 2011; Schurr et al., 2017), and the custom-made movement characteristic identification in the data processing. Despite the strengths, two limitations should be considered. First, the test sessions were non-randomized. When participants performed the conventional exercises first and then the exergames, the conventional exercises could even act as a warm-up to exergaming or conversely cause fatigue or pain toward the end, despite the low perceived exertion and pain observed during exergames. To prevent these possible effects, future studies could consider randomizing the order of the exercise protocols. Second, the number of participants was low, but nevertheless, the study showed important results in performing movement characteristics. Future studies with a higher number of participants and therefore a higher number of performed exercise protocols could provide the possibility to evaluate relationships between performed movement characteristics and elapsed time since the TKR. These aspects could be considered to provide additional knowledge to assess the appropriateness of different exergames at various stages of the rehabilitation process as well as progression demands in the exergames.

Conclusions

The results of this study showed that during custom-designed exergaming the patients with TKR achieve the movement characteristics appropriate for post-TKR rehabilitation without increasing the stress and pain experienced even though the movement characteristics might be partly different from conventional therapeutic exercises by the volume and intensity of movement. Physical therapists could consider implementing such exergames in rehabilitation practice for patients with TKR once effectiveness have been approved and they are widely available.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee of the Central Finland Health Care District. The patients/participants provided their written informed consent to participate in this study.

Author contributions

MJ, AL, SW, TP, NK, SC, JP, KP, ML, RK, TJ, AH, and EA substantially contributed to the conception and design of the work. AL, NK, ML, and EA participated in the development of exergames. MJ, JP, KP, and EA participated in the recruitment of participants. MJ, AL, TP, and EA collected the data. MJ, AL, SW, TP, and EA analyzed and interpreted the data. MJ, AL, and TP drafted the manuscript. All authors commented on the drafted manuscript and critically revised it. All authors read and approved the final manuscript.

Funding

Financial support as part of BEE research project from Business Finland and Finnish partner companies: SE Innovations Oy (Senior Some Oy), Suunto Oy, Physiotools Oy, GoodLife Technology Oy, Lingsoft Oy, eSeteli Palveluverkko Oy, PN Turku Oy, Ade Animations Design & Effects Oy, Adesante Oy, 4FeetUnder, Intechso and Realmax Oy (grant numbers: 5794/31/2016, 5941/31/2016, 6057/31/2016), and Shanghai Jiao Tong University (YG2017MS62).

Acknowledgments

The authors thank the funders, the professionals in Turku GameLab who involved in the development of the exergames, the professionals in Central Finland Central Hospital who involved in the recruitment, and the patients with TKR who participated in the study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.915210/full#supplementary-material

References

Aartolahti, E., Janhunen, M., Katajapuu, N., Paloneva, J., Pamilo, K., Keemu, H., et al. (2022). Effectiveness of gamification in knee replacement rehabilitation: protocol for a randomized controlled trial (BEE-RCT) with a qualitative approach. *JMIR Prepr*. 38434. doi: 10.2196/preprints.38434

Beswick, A. D., Wylde, V., Gooberman-Hill, R., Blom, A., and Dieppe, P. (2012). What proportion of patients report long-term pain after total hip or knee replacement for osteoarthritis? A systematic review of Prospective studies in unselected patients. *BMJ Open* 2, 1–12. doi: 10.1136/bmjopen-2011-000435

Borg, G. (1982). Psychophysical bases of perceived exertion. *Med. Sci. Sports Exerc.* 14, 377–381. doi: 10.1249/00005768-198205000-00012

Bruyère, O., Honvo, G., Veronese, N., Arden, N. K., Branco, J., Curtis, E. M., et al. (2019). An updated algorithm recommendation for the management of knee osteoarthritis from the European Society for Clinical and Economic Aspects of Osteoporosis, Osteoarthritis and Musculoskeletal Diseases (ESCEO). *Semin. Arthritis Rheum.* 49, 337–350. doi: 10.1016/j.semarthrit.2019.04.008

Christiansen, C. L., Bade, M. J., Weitzenkamp, D. A., and Stevens-Lapsley, J. E. (2013). Factors predicting weight-bearing asymmetry 1 month after unilateral total knee arthroplasty: a cross-sectional study. *Gait Post.* 37, 363–367. doi: 10.1016/j.gaitpost.2012.08.006

Corregidor-Sánchez, A. I., Segura-Fragoso, A., Rodríguez-Hernández, M., Jiménez-Rojas, C., Polonio-López, B., Criado-Álvarez, J. J., et al. (2021). Effectiveness of virtual reality technology on functional mobility of older adults: systematic review and meta-analysis. *Age Ageing* 50, 1–10. doi: 10.1093/ageing/afaa197

da Cruz, M. M. A., Ricci-Vitor, A. L., Borges, G. L. B., da Silva, P. F., Ribeiro, F., and Vanderlei, L. C. M. (2020). Acute hemodynamic effects of virtual reality–based therapy in patients of cardiovascular rehabilitation: a cluster randomized crossover trial. *Arch. Phys. Med. Rehabil.* 101, 642–649. doi: 10.1016/j.apmr.2019.12.006

de Vries, A. W., Faber, G., Jonkers, I., Van Dieen, J. H., and Verschueren, S. M. (2018). Gait & posture virtual reality balance training for elderly : similar skiing games elicit different challenges in balance training. *Gait Post.* 59, 111–116. doi: 10.1016/j.gaitpost.2017.10.006

Dulau, E., Botha-Ravyse, C. R., and Luimula, M. (2019). "Virtual reality for physical rehabilitation: a Pilot study how will virtual reality change physical therapy?," in *10th IEEE International Conference on Cognitive Infocommunications, CogInfoCom 2019 – Proceedings*, (Naples: IEEE), 277–282. doi: 10.1109/CogInfoCom47531.2019.9089980

Elliott, B. C., Alderson, J. A., and Denver, E. R. (2007). System and modelling errors in motion analysis: implications for the measurement of the elbow angle in cricket bowling. *J. Biomech.* 40, 12. doi: 10.1016/j.jbiomech.2006.12.012

Gogia, P. P., Braatz, J. H., Rose, S. J., and Norton, B. J. (1987). Reliability and validity of goniometric measurements at the knee. *Phys. Ther.* 67, 2. doi: 10.1093/ptj/67.2.192

Hevner, A. R., March, S. T., Park, J., and Ram, S. (2004). Design science in information systems research. *MIS Q Manag. Inf. Syst.* 28, 75–105. doi: 10.2307/25148625

Jensen, M. P., Chen, C., and Brugger, A. M. (2003). Interpretation of visual analog scale ratings and change scores: a reanalysis of two clinical trials of postoperative pain. *J. Pain* 4, 7. doi: 10.1016/S1526-5900(03)00716-8

Jette, D. U., Hunter, S. J., Burkett, L., Langham, B., David, S., Piuzzi, N. S., et al. (2020). Physical therapist management of total knee arthroplasty. *Phys. Ther.* 100, 1603–1631. doi: 10.1093/ptj/pzaa099

Kinovea (2021). Available online at: https://www.kinovea.org/ (accessed April 9, 2021).

Lenssen, A. F., Van Dam, E. M., Crijns, Y. H. F., Verhey, M., Geesink, R. J. T., Van Den Brandt, P. A., et al. (2007). Reproducibility of goniometric measurement of the knee in the in-hospital phase following total knee arthroplasty. *BMC Musculoskelet. Disord.* 8, 83. doi: 10.1186/1471-2474-8-83

McConnell, S., Kolopack, P., and Davis, A. M. (2001). The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC): a review of its utility and measurement properties. *Arthrit. Care Res.* 45, 453–461, doi: 10.1002/1529-0131(200110)45:5<453::AID-ART365>3.0.CO;2-W

National Institute for Health and Welfare (2021). *Finnish Arthoplasty* Register. Available online at: https://www.thl.fi/far/#index (accessed July 26, 2021).

Norris, B. S., and Olson, S. L. (2011). Concurrent validity and reliability of two-dimensional video analysis of hip and knee joint motion during mechanical lifting. *Physiother. Theory Pract.* 27, 521–530. doi: 10.3109/09593985.2010.533745

Oh, Y., and Yang, S. P. (2010). "Defining exergames & exergaming," in *Meaningful Play*. Available online at: https://meaningfulplay.msu.edu/proceedings2010/mp2010_paper_63.pdf (accessed December 3, 2021).

Papalia, R., Campi, S., Vorini, F., Zampogna, B., Vasta, S., Papalia, G., et al. (2020). The role of physical activity and rehabilitation following hip and knee arthroplasty in the elderly. *J. Clin. Med.* 9, 1–12. doi: 10.3390/jcm9051401

Pirovano, M., Surer, E., Mainetti, R., Lanzi, P. L., and Borghese, N. A. (2016). Exergaming and rehabilitation: a methodology for the design of effective and safe therapeutic exergames. *Entertain. Comput.* 14, 55–65. doi: 10.1016/j.entcom.2015.10.002

Pyae, A., Liukkonen, T. N., Luimula, M., Kattimeri, C., Cauberghe, V., Smed, J., et al. (2017). Investigating the Finnish elderly people's attitudes and motivation towards digital game-based physical exercises. *Finnish J eHealth eWelfare* 9, 265–283. doi: 10.23996/fjhw.60518

R Core Team (2020). *R: A Language and Environment for Statistical Computing*. Available online at: https://www.r-project.org/ (accessed December 3, 2020).

Rowe, P. J., Myles, C. M., Walker, C., and Nutton, R. (2000). Knee joint kinematics in gait and other functional activities measured using flexible electrogoniometry: how much knee motion is sufficient for normal daily life? *Gait Post.* 12, 143–155. doi: 10.1016/S0966-6362(00)00060-6

Schreven, S., Beek, P. J., and Smeets, J. B. J. (2015). Optimising filtering parameters for a 3D motion analysis system. *J. Electromyogr. Kinesiol.* 25, 5. doi: 10.1016/j.jelekin.2015.06.004

Schurr, S. A., Marshall, A. N., Resch, J. E., and Saliba, S. A. (2017). Two-dimensional video analysis is comparable to 3d motion capture in lower extremity movement assessment. *Int. J. Sports Phys. Ther.* 12, 163–172. doi: 10.1186/s12891-015-0469-6

Skjæret, N., Nawaz, A., Morat, T., Schoene, D., Helbostad, J. L., Vereijken, B., et al. (2016). Exercise and rehabilitation delivered through exergames in older adults: an integrative review of technologies, safety and efficacy. *Int. J. Med. Inform.* 85, 1–16. doi: 10.1016/j.ijmedinf.2015.10.008

Skjæret-Maroni, N., Vonstad, E. K., Ihlen, E. A. F., Tan, X. C., Helbostad, J. L., Vereijken, B., et al. (2016). Exergaming in older adults: movement characteristics while playing stepping games. *Front. Psychol.* 7, 964. doi: 10.3389/fpsyg.2016.00964

South West Finland Health Care District (2015). *Guidebook for Knee Replacement Patients* (in Finnish). Tallinn: SpinPress, 16.

Tahmosybayat, R., Baker, K., Godfrey, A., Caplan, N., and Barry, G. (2018). Movements of older adults during exergaming interventions that are associated with the systems framework for postural control: a systematic review. *Maturitas* 111, 90–99. doi: 10.1016/j.maturitas.2018.03.005

Thong, I. S. K., Jensen, M. P., Miró, J., and Tan, G. (2018). The validity of pain intensity measures: What do the NRS, VAS, VRS, and FPS-R measure? *Scand, J. Pain* 18, 1. doi: 10.1515/sjpain-2018-0012

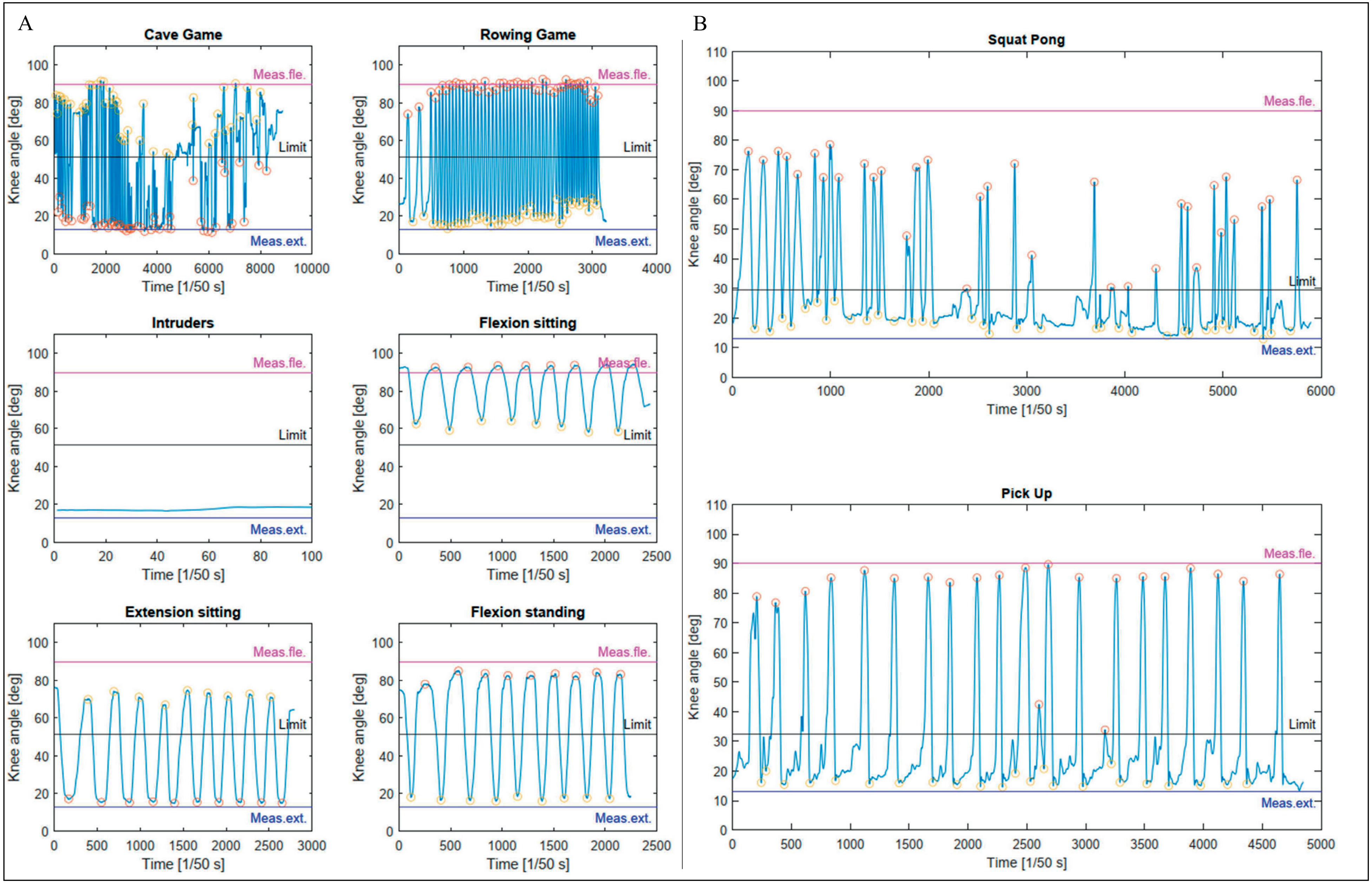
Tsuzuku, S., Kajioka, T., Sakakibara, H., and Shimaoka, K. (2018). Slow movement resistance training using body weight improves muscle mass in the elderly: a randomized controlled trial. *Scand. J. Med. Sci. Sport* 28, 1339–1344. doi: 10.1111/sms.13039

Wang, X., Hunter, D. J., Vesentini, G., Pozzobon, D., and Ferreira, M. L. (2019). Technology-assisted rehabilitation following total knee or hip replacement for people with osteoarthritis: a systematic review and meta-analysis. *BMC Musculoskelet. Disord.* 20, 1–17. doi: 10.1186/s12891-019-2900-x

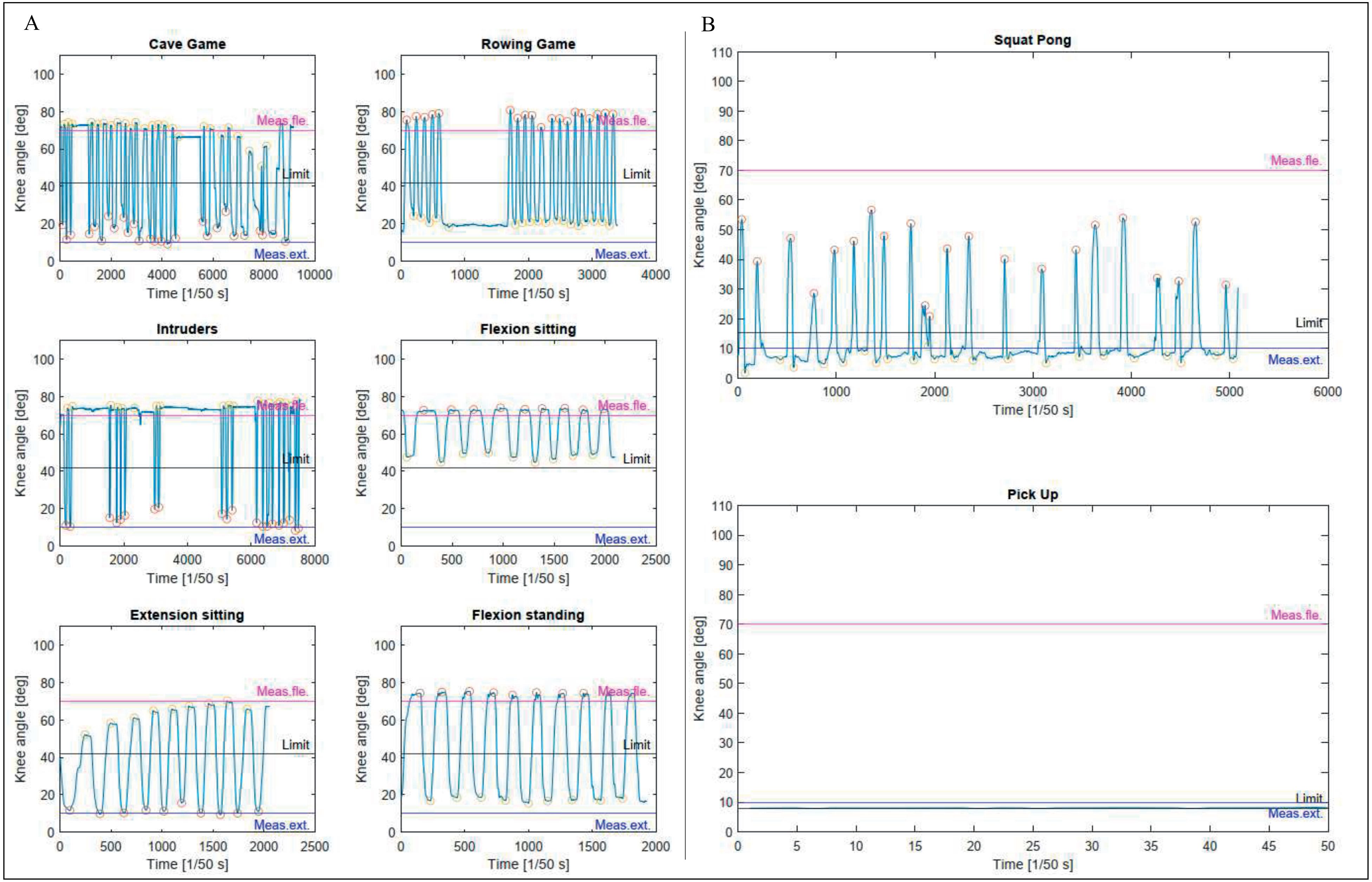
Willaert, J., De Vries, A. W., Tavernier, J., Van Dieen, J. H., Jonkers, I., and Verschueren, S. (2020). A novel exergame challenge balance and activate muscles more than existing off-the-shelf exergames? *J. Neuroeng. Rehabil.* 17, 1–13. doi: 10.1186/s12984-019-0628-3

Zadro, J. R., Shirley, D., Simic, M., Mousavi, S. J., Ceprnja, D., Maka, K., et al. (2019). Video-game–based exercises for older people with chronic low back pain: a randomized controlled trial (GAMEBACK). *Phys. Ther.* 99, 14–27. doi: 10.1093/ptj/pzy112

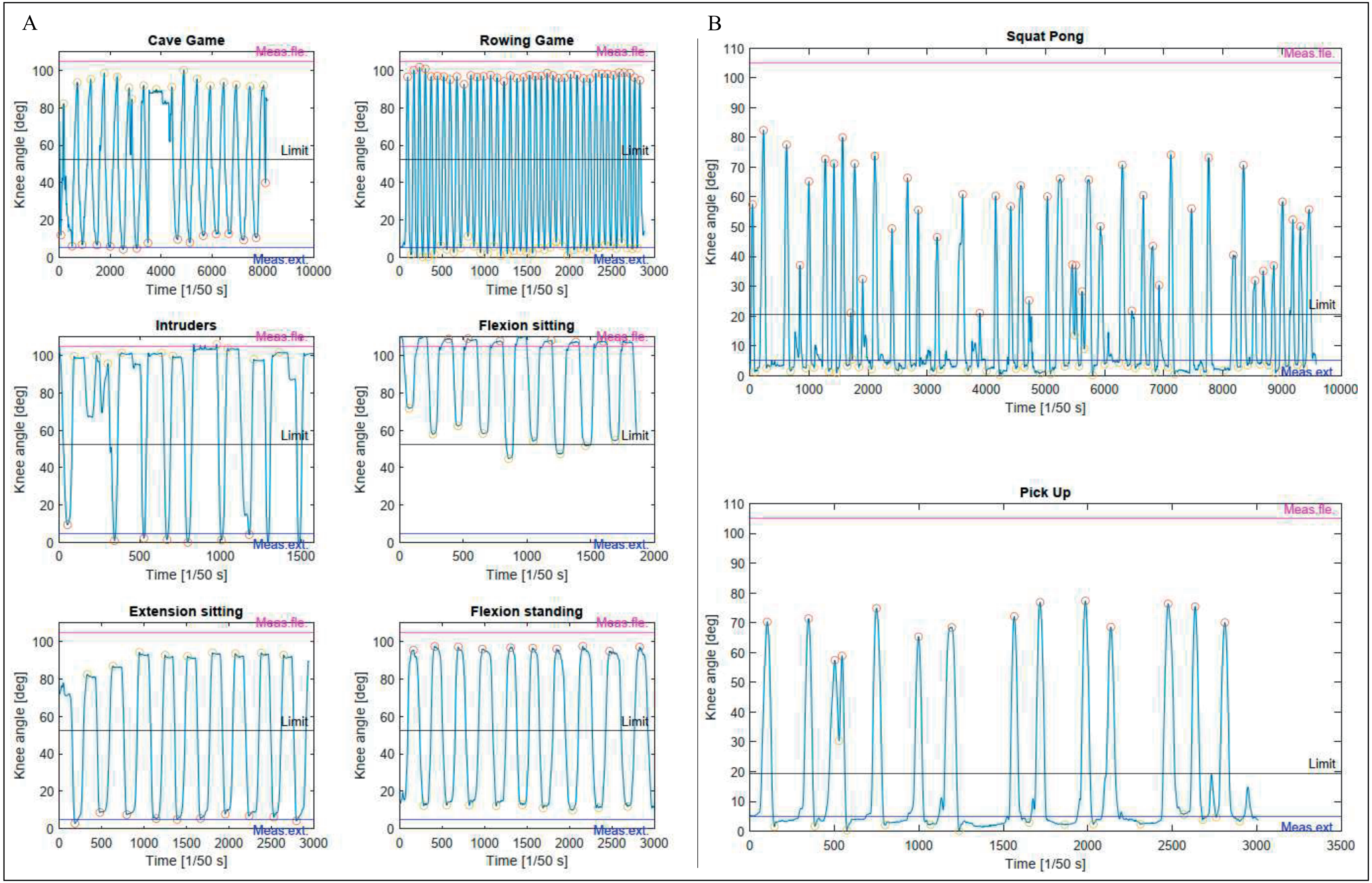
Zeni, J., Abujaber, S., Flowers, P., Pozzi, F., and Snyder-Mackler, L. (2013). Biofeedback to promote movement symmetry after total knee arthroplasty: a feasibility study. *J. Orthop. Sport Phys. Ther.* 43, 715–726. doi: 10.2519/jospt.2013.4657



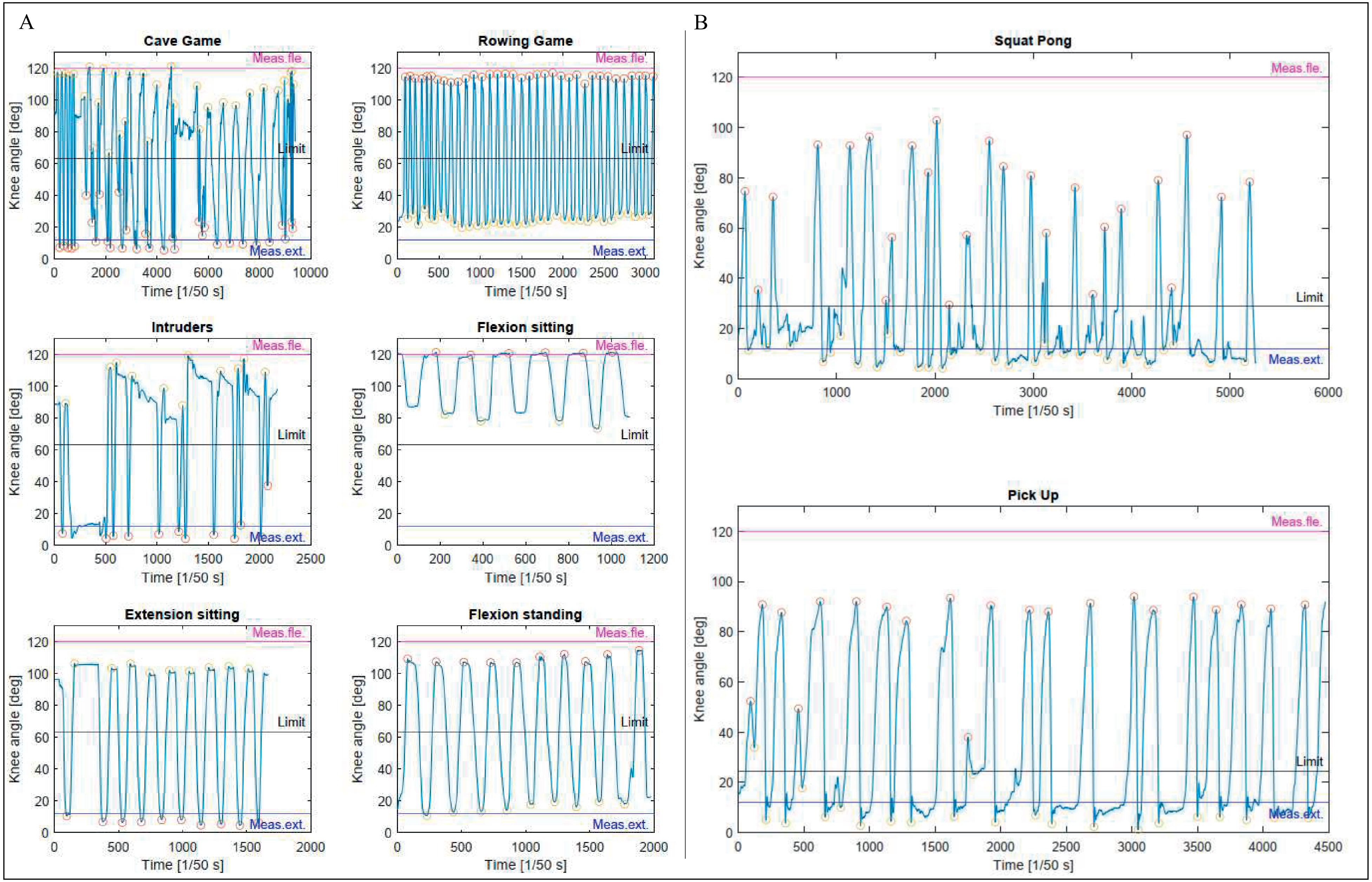
Supplementary Figure 1. Participant 1: Knee angle during knee extension and flexion games (A) and exergames with squatting movement (B).



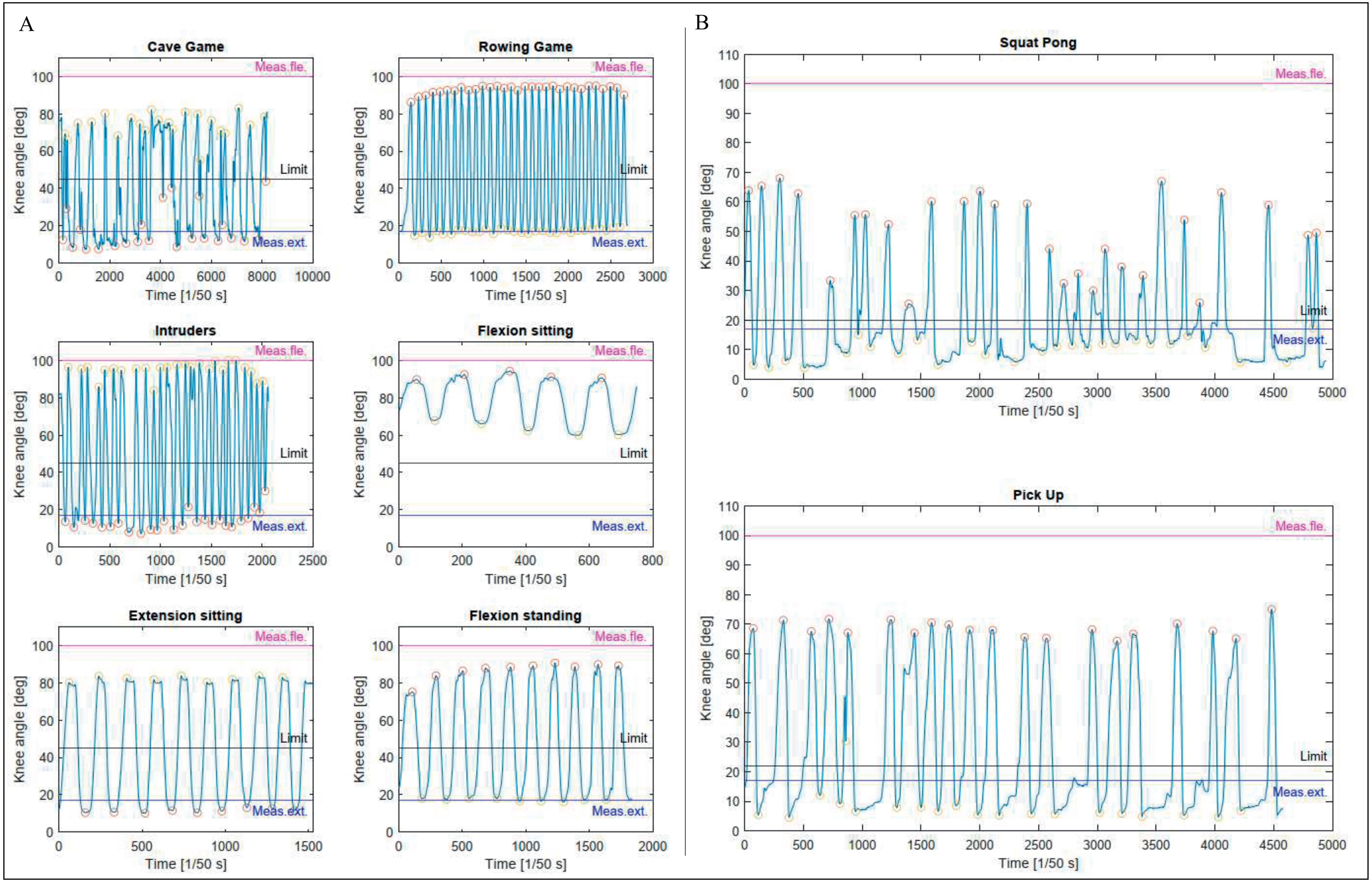
Supplementary Figure 2. Participant 2: Knee angle during knee extension and flexion games (A) and exergames with squatting movement (B).



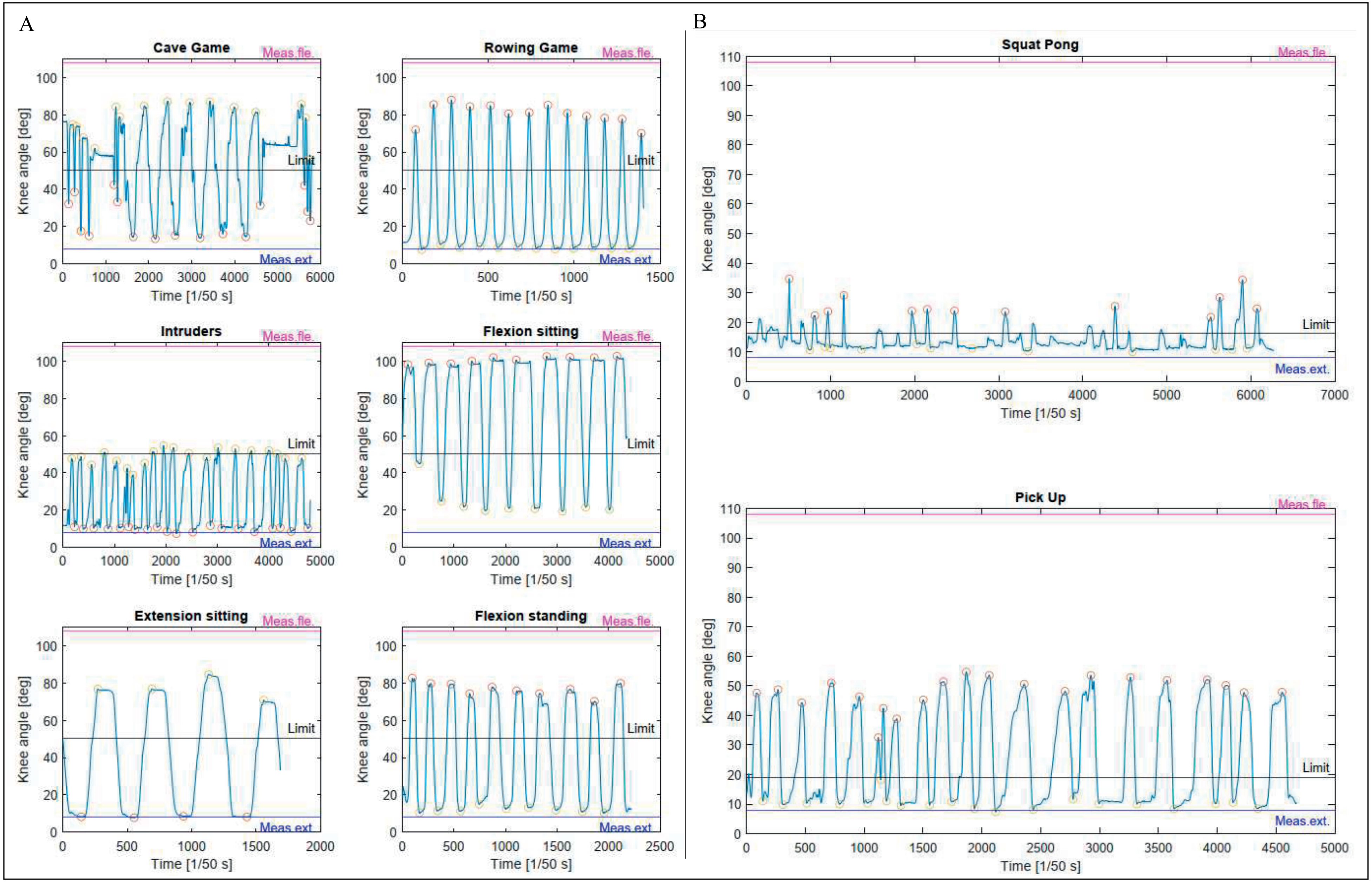
Supplementary Figure 3. Participant 3: Knee angle during knee extension and flexion games (A) and exergames with squatting movement (B).



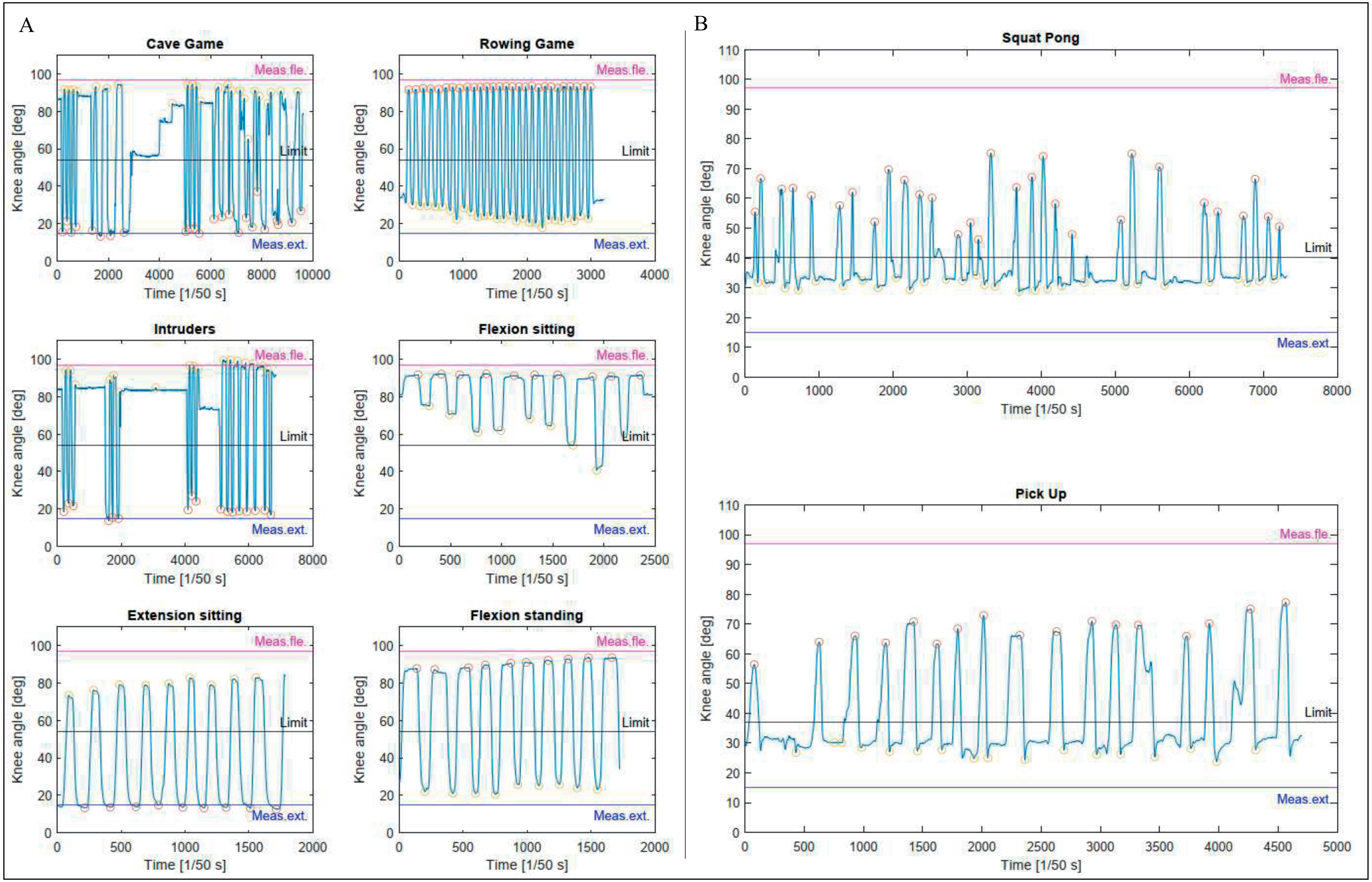
Supplementary Figure 4. Participant 4: Knee angle during knee extension and flexion games (A) and exergames with squatting movement (B).



Supplementary Figure 5. Participant 5: Knee angle during knee extension and flexion games (A) and exergames with squatting movement (B).



Supplementary Figure 6. Participant 6: Knee angle during knee extension and flexion games (A) and exergames with squatting movement (B).



Supplementary Figure 7. Participant 7: Knee angle during knee extension and flexion games (A) and exergames with squatting movement (B).

II

EFFECTIVENESS OF EXERGAME INTERVENTION ON WALKING IN OLDER ADULTS: A SYSTEMATIC REVIEW AND META-ANALYSIS OF RANDOMIZED CONTROLLED TRIALS

by

Maarit Janhunen, Vera Karner, Niina Katajapuu, Oona Niiranen, Jaakko Immonen, Juha Karvanen, Ari Heinonen & Eeva Aartolahti, 2021

Physical Therapy & Rehabilitation Journal 101 (9), 1-11

https://doi.org/10.1093/ptj/pzab152

PTJ: Physical Therapy & Rehabilitation Journal | *Physical Therapy*, 2021;101:1–11
https://doi.org/10.1093/ptj/pzab152
Advance access publication date June 21, 2021
Review

Effectiveness of Exergame Intervention on Walking in Older Adults: A Systematic Review and Meta-Analysis of Randomized Controlled Trials

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Abstract

Objective. The objective of this review was to systematically evaluate the effectiveness of exergaming on walking in older adults. In addition, the aim was to investigate the relationship between the exergaming effect and age, baseline walking performance, exercise traits, technology used, and the risk of bias.

Methods. A literature search was carried out in the databases MEDLINE, CINAHL, CENTRAL, EMBASE, WoS, PsycInfo, and PEDro up to January 10, 2020. Studies with a randomized controlled trial design, people ≥60 years of age without neurological disorders, comparison group with other exercise or no exercise, and walking-related outcomes were included. Cochrane RoB2, meta-analysis, meta-regression, and Grading of Recommendations, Assessment, Development and Evaluation were used to estimate quality, treatment effect, covariates' effect, and the certainty of evidence, respectively.

Results. In the studies included (n = 66), the overall risk of bias was low (n = 2), unclear (n = 48), or high (n = 16). Compared with comparison groups, exergaming interventions were more effective for walking improvements (standardized mean difference = −0.21; 95% CI = −0.36 to −0.06; 3102 participants, 58 studies; moderate-quality evidence) and more or equally effective (standardized mean difference = −0.32; 95% CI = −0.64 to 0.00; 1028 participants, 13 studies; low-quality evidence) after nonexergaming follow-up. The strongest effect for covariates was observed with the type of comparison group, explaining 18.6% of the variance.

Conclusion. For older adults without neurological disorders, exergame-based training improved walking, and improvements were maintained at follow-up. Greater benefits were observed when exergaming groups were compared with inactive comparison groups. To strengthen the evidence, further randomized controlled trials on the effectiveness of gamified exercise intervention are needed.

Impact. Exergaming has an effect equivalent to other types of exercising on improving walking in older adults. Physical therapists and other rehabilitation professionals may consider exergaming as a promising form of exercise in this age group.

Keywords: Aged, Exercise Therapy, Exergames, Rehabilitation, Walking

Received: October 15, 2020. **Revised:** February 19, 2021. **Accepted:** May 5, 2021

Introduction

Walking is the leading form of mobility for older adults. It is one of the main areas of physical functioning that enables physical activity and independence,[1] social participation,[2] and good quality of life[3] in older adults. Adequate physical activity that includes walking lowers the risk of major mobility disability among older adults.[4,5] Evidence demonstrates that physical activity and exercise reduce the risk of age-related loss of physical functioning[6] and multicomponent training, including strength and balance training, improves or maintains walking in older adults.[7,8] One novel multicomponent training method that may be used to enhance walking is exercise games, known as exergames.

Exergames, also considered serious games, are computer-based video games that can be used for nonrecreational purposes, such as for physical rehabilitation targeting to correct and to restore musculoskeletal functions.[9] Exergaming requires physical performance from the player, as the technology used in gaming system tracks the player's physical movements to control the game, immersing the player in the game. In rehabilitation, exergaming may be targeted to enhance the physical functioning, such as walking performance,[10] of different patient groups,[11] and it may be carried out in a variety of settings, such as in unsupervised conditions.[12,13] Exercising with exergames has been shown to be engaging[14] and enjoyable[15] among older adults and thus may increase training volume and contribute to the effectiveness of physical rehabilitation.

The scientific interest in exergaming as a potential rehabilitation method in older adults has grown with the increase of digitalization in physical rehabilitation.[9] Evidence shows that exergaming is effective in improving walking in older adults with neurologic disorders.[16] In addition, a positive effect on walking has been observed in older adults with no specific pathologies, but the evidence is based on pooled outcomes of physical performance[10,17] or a variety of study designs, including non-randomized controlled trials (RCTs).[18] To the best of our knowledge, no previous meta-analysis of RCTs has solely focused on walking in older adults without neurological disorders. Therefore, the aim of this meta-analysis was to summarize studies with an RCT design investigating the effectiveness of exergame-based intervention on walking in older adults without neurological disorders and to implement meta-regression to account for a risk of bias and heterogeneity in studies. The following questions were addressed: (1) Are exergame-based interventions more effective than comparison group interventions on walking in older adults? (2) Does participants' age, baseline walking performance, duration of intervention, setting of intervention, number of sessions per week, duration of single session, type of comparison group, technology used, or risk of bias explain the effectiveness of exergame-based training on walking?

Methods

This systematic review and meta-analysis of RCTs was registered prospectively in the International Prospective Register of Systematic Reviews (https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42020148701) before completion of formal screening of search results against eligibility criteria and starting the data extraction. The reporting corresponds to the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses.[19]

To study the effectiveness of computer-based exercise interventions on walking, only RCTs were included in the review. The eligibility criteria followed the PICO framework; participants were 60 years or older (P), experimental intervention was carried out with exergames that demanded physical movements (I), the comparison group had a different type of exercising protocol (active control) or no exercise protocol (inactive control) (C), and the study reported validated and standardized outcomes measuring walking (O). Theses and conference proceeding abstracts, studies focusing on patients with neurological disorders (such as stroke, Parkinson's disease, or multiple sclerosis), studies using accelerometers or actual locations in the intervention to encourage and to record physical activity (eg, pedometers, Pokémon Go), and studies of exergames driven by player's eyes, head, or fine physical movements were excluded from the review. No language or publication date restrictions were applied.

Data Sources and Searches

RCTs were identified by searching 7 electronic databases in January 2019 and January 2020 (updated search) covering the earliest available date until January 10, 2020. The databases were US National Library of Medicine (MEDLINE, 1946 to present), Cumulative Index to Nursing and Allied Health Literature (CINAHL, 1981 to present), Cochrane Central Register of Controlled Trials (CENTRAL, 1991 to present), Comprehensive Biomedical Literature Database (EMBASE, 1947 to present), Web of Science (WoS, 1945 to present), Behavioral and Social Science Research (PsycInfo, 1887 to present), and Physiotherapy Evidence Database (PEDro, 1929 to present). In addition, research article publications were monitored from the review's topic.

The key terms used to identify studies in the electronic search were exergame, exercise, and RCT. Synonyms, MeSH, and related terms of key terms (eg, video games for exergame, physical rehabilitation for exercise, and clinical trial for RCT) and RCT filters (MEDLINE [Ovid], Embase and CINAHL [Ebsco],[20] Web of Science[21]) were combined by using the Boolean operators "OR" and "AND." A full electronic search strategy in the MEDLINE database is presented in Supplementary Material A.

Study Selection

References of identified studies were imported to the screening and data extraction tool[22] in which duplicates were removed from the search results. Authors (M.J., V.K., N.K., O.N., and E.A.) in pairs independently assessed study titles and abstracts by applying the eligibility criteria. Research reports were collected for studies that were carried forward to the full-text screening. The pairs of authors independently reapplied eligibility criteria to full texts and reported reasons for the exclusion of ineligible studies. In the screening, disagreement between the pairs of authors was resolved by discussion between them or by the third author (M.J., N.K., or E.A.). All eligible RCTs were included in the systematic review and, if applicable, in the meta-analysis.

Data Extraction and Quality Assessment

A customized format to report participants, interventions, and outcomes of studies included in the data extraction was created (M.J.) (Suppl. Material A), and the Cochrane Risk of Bias 2 tool[23] was used in the quality assessment of individual studies at the outcome level. Before starting the data extraction and quality assessment, joint practice among the team of reviewing authors was conducted to ensure uniform data extraction and risk of bias evaluation. Two authors (M.J. and either V.K., N.K, O.N., or E.A.) performed the data extraction and risk of bias evaluation independently. When necessary, disagreements between the 2 authors in the evaluations were resolved by discussion between them or by a third independent author (E.A.).

Eighteen original researchers were contacted no more than 3 times via email and ResearchGate because of inadequate participant (2) or outcome data (14) and ambiguities (2) found in the published papers. Eleven of them responded and provided participant and outcome data (1 and 10, respectively) (Suppl. Material A). Journal articles, trial protocols, and trial registry records were used in risk of bias assessments, with a focus on the effect of assignment to intervention (the intention-to-treat effect). All studies, regardless of risk of bias judgement, were included in the narrative synthesis and the meta-analysis.

Data Synthesis and Analysis

Improvement in walking was the primary measure of treatment effect. To assess the treatment effect after intervention and when available after follow-up periods, the meta-analysis was performed in R[24] with the metafor package[25] using a random effects model and restricted maximum-likelihood estimation. In the quantitative synthesis, post-intervention and follow-up mean and SD values of continuous outcomes were used to calculate standardized mean differences (SMD, Hedges' g) and 95% CIs between groups. The effect size was considered small ($g = 0.2$), medium ($g = 0.5$), or large ($g = 0.8$).[26]

For studies in which the mean and SD were not reported (n = 7), SMDs were calculated according to recommendations[27] (Suppl. Material A). When post-intervention values were not available or the study had subgroups that did not match the review's inclusion criteria, changes from baseline values and a subset of data were used in the meta-analysis and the meta-regression. For studies with multiple comparator groups, the dependency structure of the SMDs was taken into account in the variance–covariance matrix.[28] The Grading of Recommendations, Assessment, Development and Evaluation[29] was used to rate the certainty of evidence in the meta-analysis.

Synthesis was structured around the content of interventions and outcomes, the latter being prioritized according to incidence level, validity, and reliability to define a direction of the value (lower/higher is better) and to combine results from studies in the analysis (Suppl. Material A). Heterogeneity was explored with the Q and I^2 statistic and assessed from forest and funnel plots.

Risk of Bias Across Studies

Bias caused by selective publication within studies was evaluated by assessing the funnel plot of the trial mean differences for asymmetry.[30] The bias caused by selective reporting within studies was evaluated from the risk of bias assessment.

Meta-Regression

Meta-regression was conducted to assess high risk of bias and sources of heterogeneity between studies. The covariates included in the meta-regression were participants' mean age and level of walking performance prior intervention, duration and setting (unsupervised) of intervention, number of sessions per week, session duration, type of comparison group (active or inactive), technology used (made for physical rehabilitation purposes), and risk of bias domains (high risk). Participants' walking performance prior to intervention was evaluated from their baseline Timed Up & Go (TUG) test results. A separate meta-regression model was fitted for each covariate. In addition, a model including all covariates simultaneously was fitted. Heterogeneity accounted for by the covariates was measured using (pseudo) R^2.[31]

Multiple Imputation

To avoid excluding studies from the meta-regression, multiple imputation was applied to the study-level covariates that were not measured in some of the studies. These variables included the TUG test, walking speed (calculated from a 2-minute walking test or from a 6-minute walking test), the number of sessions per week, and the session duration. The imputation model for the TUG test was a log-linear model, where the logarithm of the TUG test result was explained by participants' mean age and the logarithm of the walking speed. The roles of the TUG test and the walking speed were exchanged when the walking speed was imputed. Multiple imputation by chained equations[32] and the R package mice[33] were used.

Role of the Funding Source

The funders played no role in the design, conduct, or reporting of this study.

Results

Study Selection and Characteristics

The search yielded 6534 studies (Fig. 1). After removal of duplicates and studies considered ineligible according to the PICOS criteria, 66 RCTs were included in the review (Fig. 1), and 58 RCTs were included in the meta-analysis (Fig. 2) and in the meta-regression (Tab. 1). Lists of the references of included and excluded studies and justifications for exclusions are included in Supplementary Material B. Detailed study characteristics of RCTs included in the qualitative synthesis are summarized in Supplementary Material C. The RCTs selected for the review were published in English, except for 1 in Spanish.[34]

Participants

The included studies involved 3774 participants. The range of sample sizes was from 6 to 508 (mean = 27.8, SD = 125.5) in the experimental groups and from 5 to 469 (mean = 19.2, SD = 116.0) in the comparison groups. When gender was reported, the percentage of women ranged from 0.0% to 100.0% (mean = 60.5%, SD = 25.0 in experimental group and mean = 59.2%, SD = 25.0 in comparison groups). The participants' ages ranged from 60.5 to 87.5 years (mean = 74.3, SD = 6.8). In several studies included in the review, participant group was community-dwelling or independently living (n = 26). In other studies, participant groups were older adults with chronic disease (n = 14), mild cognitive impairment (n = 6), balance or mobility difficulties (n = 7), or participants were hospitalized or living in assistive facilities (n = 5), prefrail or frail (n = 5), sedentary (n = 2), or patients in rehabilitation or primary care centers (n = 2).

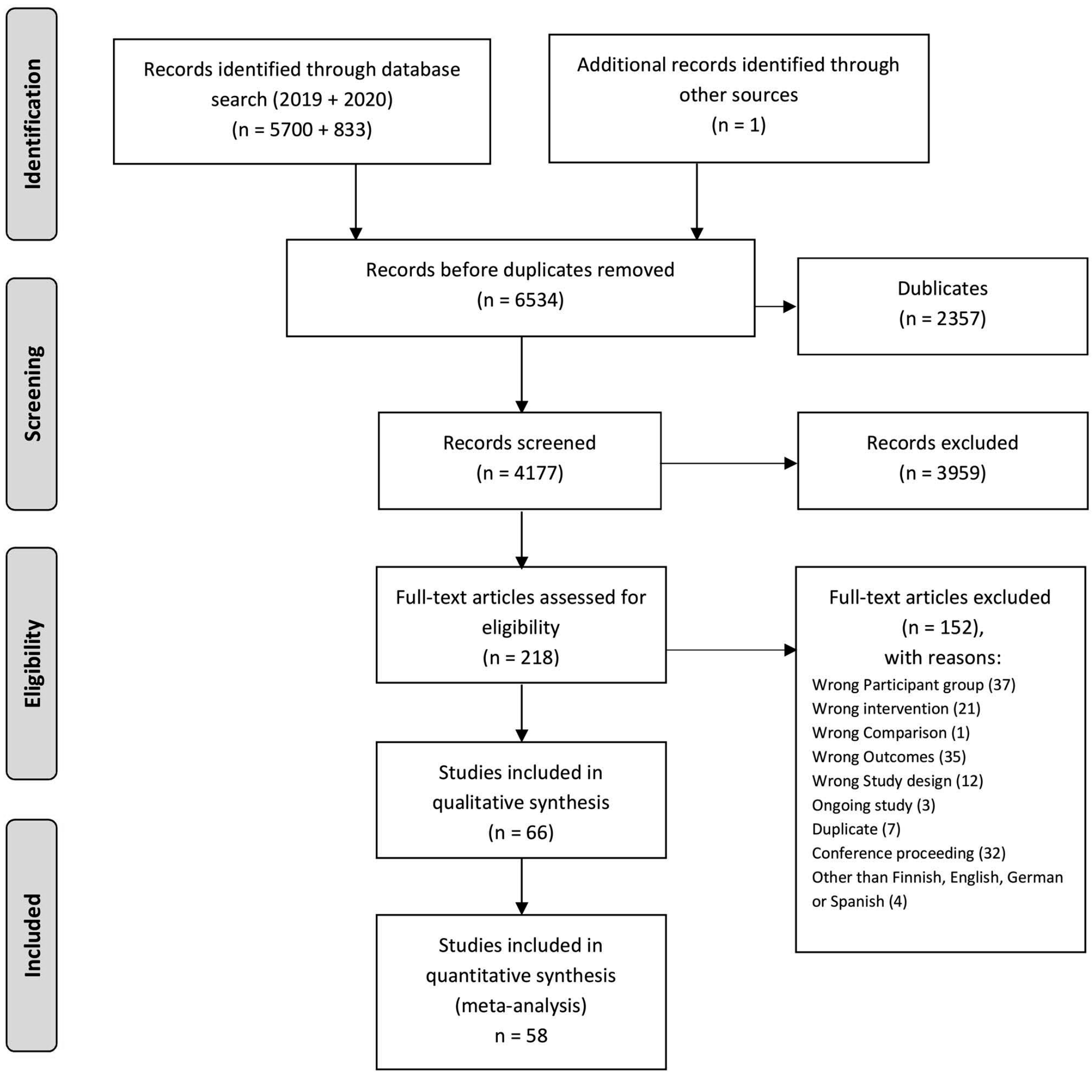

Figure 1. Study selection strategy flow chart.

Interventions

Interventions were carried out at the hospital (n = 9), laboratory (n = 16), outpatient clinic (n = 11), day or welfare center or similar (n = 7), participants' home (n = 16), or care home, assisted living facility, or similar (n = 11). The duration of interventions ranged from 2 to 26 (mean = 9, SD = 6.0) weeks with 1 to 11 (mean = 3, SD = 2) sessions per week, 11 to 90 (mean = 44, SD = 20) minutes per session. In the meta-regression, the mean value of sessions per week was used in 2 studies[35,36] in which weekly sessions were reported as minimum sessions per week. In 12.3% of interventions, exergaming was performed in addition to other exercising. The games used in the interventions were based on technology developed to rehabilitate physical functioning (30.8%), or the games were commercially available (69.2%), such as the Nintendo Wii or the Xbox 360. In 80.0% of interventions, exergaming was supervised. Descriptions of exergame protocols and technologies used are described in Supplementary Material C. Sixteen studies had a follow-up period. Among them, 2 RCTs were excluded from the meta-analysis because walking outcomes were not remeasured after the follow-up period (Suppl. Material B). The duration of the follow-up period ranged from 3 to 36 (mean = 14, SD = 8) weeks.

Comparison

In 49 studies, the comparison group had other exergaming protocols or different exercising protocols, such as resistance and balance training or training with cognitive tasks (ie, active control). In 30 studies, the comparison group did not have an exercise protocol (ie, inactive control), but the group received health education, played cognitive games such as table and card games, used insoles, or continued their usual daily activities.

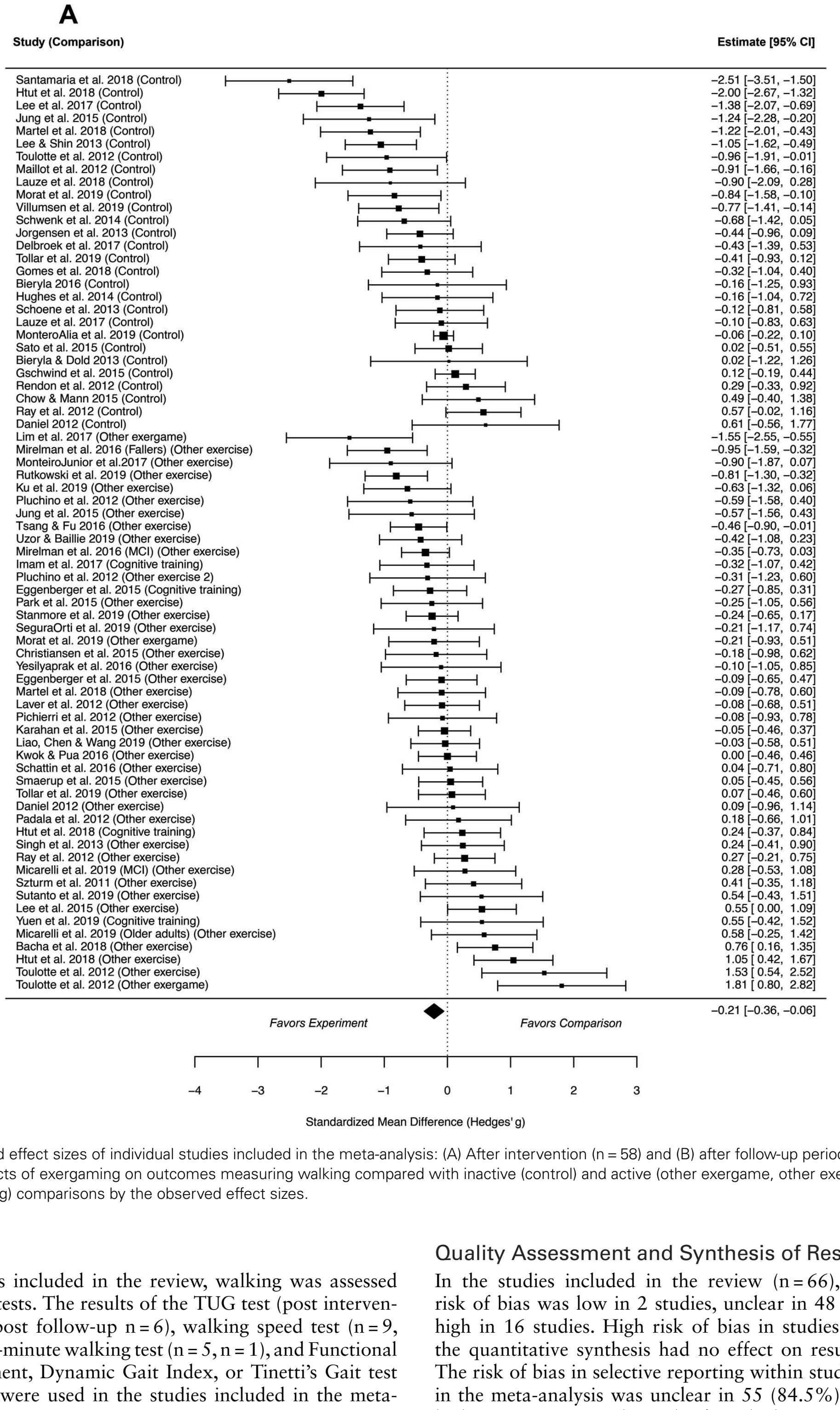

Figure 2. Pooled effect sizes of individual studies included in the meta-analysis: (A) After intervention (n = 58) and (B) after follow-up period (n = 13). Analysis of effects of exergaming on outcomes measuring walking compared with inactive (control) and active (other exergame, other exercise, cognitive training) comparisons by the observed effect sizes.

Outcomes

In the studies included in the review, walking was assessed with several tests. The results of the TUG test (post intervention n = 38, post follow-up n = 6), walking speed test (n = 9, n = 4), 2- or 6-minute walking test (n = 5, n = 1), and Functional Gait Assessment, Dynamic Gait Index, or Tinetti's Gait test (n = 6, n = 2) were used in the studies included in the meta-analysis.

Quality Assessment and Synthesis of Results

In the studies included in the review (n = 66), the overall risk of bias was low in 2 studies, unclear in 48 studies, and high in 16 studies. High risk of bias in studies included in the quantitative synthesis had no effect on results (Tab. 1). The risk of bias in selective reporting within studies included in the meta-analysis was unclear in 55 (84.5%) studies and high in 3 (3.4%) studies. The funnel plots (Fig. 3) showed

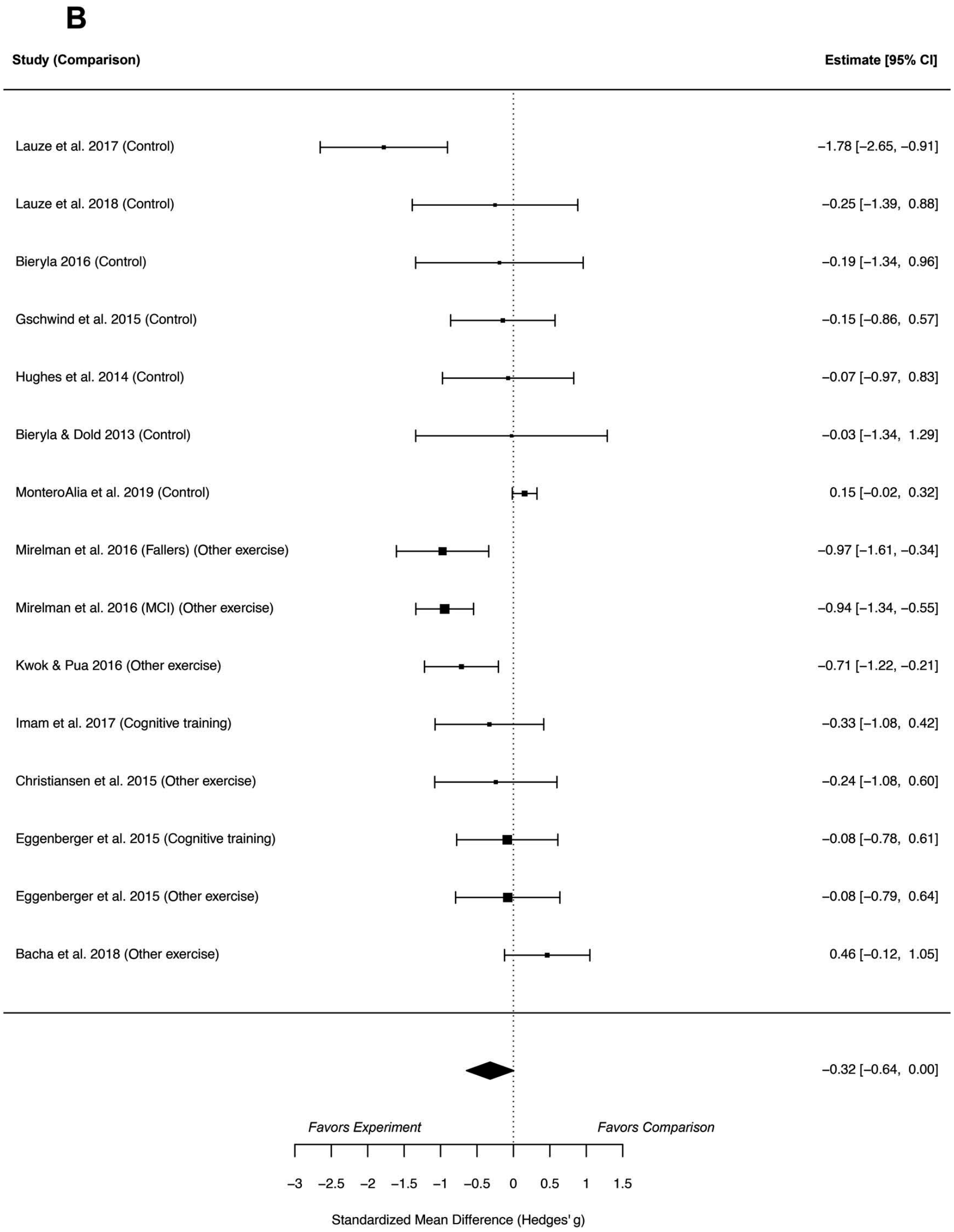

Figure 2. Continued.

the possibility of publication bias of smaller studies favoring the experimental group. Certainty of evidence assessed with Grading of Recommendations, Assessment, Development and Evaluation was lowered because of inconsistency and imprecision within studies. The assessment is presented in the "Summary of Findings" table. The risk of bias assessments and the "Summary of Findings" table are presented in Supplementary Material C. In the multi-imputation, participants' mean age and the logarithm of the walking speed explained 92% of the variation in the logarithm of the TUG test result in the complete cases.

After Intervention

Compared with active and inactive comparisons, exergaming had a small but significant effect on the improvement in walking (SMD = −0.21, 95% CI = −0.36 to −0.06; 3102 participants, 58 studies; moderate-quality evidence) (Fig. 2). Heterogeneity was substantial ($Q = 245.18$, $P < .0001$,

Table 1. Results of the Meta-regression Analysis on Covariates Concerning the Study Factors (Group 1) and the High Risk of Bias Domains (Group 2)[a]

Group	Covariates	Model 1[b]					Model 2[c]				
		Estimated Effect Size	Lower CI	Upper CI	*P*	R^2 (%)[d]	Estimated Effect Size	Lower CI	Upper CI	*P*	R^2 (%)[d]
1	Age	0.01	−0.02	0.03	.64	0.0	0.01	−0.03	0.04	.57	14.1
	Walking performance before intervention	0.01	−0.02	0.04	.65	0.0	0.00	−0.04	0.04	.90	
	Intervention duration	0.02	−0.01	0.05	.15	0.6	0.03	−0.01	0.06	.10	
	Setting (unsupervised exergaming)	0.03	−0.35	0.41	.87	0.0	0.06	−0.33	0.45	.76	
	Sessions per week	0.05	−0.08	0.17	.45	0.0	0.07	−0.05	0.19	.26	
	Session duration	0.00	−0.01	0.01	.71	0.0	0.00	−0.02	0.01	.57	
	Type of comparison group (active/inactive)	0.48	0.20	0.77	<.001	18.6	0.50	0.19	0.81	.002	
	Technology used developed for physical rehabilitation	−0.14	−0.48	0.20	.42	0.0	−0.19	−0.53	0.16	.29	
2	Randomization process	0.27	−0.28	0.81	.34	0.0	−1.07	−1.96	−0.18	.02	27.0
	Deviations from intended interventions	0.13	−0.25	0.52	.50	0.0	−0.78	−1.45	−0.11	.02	26.0
	Missing outcome data	0.11	−0.44	0.67	.69	0.0	−1.08	−2.03	−0.14	.02	25.1
	Selection of reported results	0.16	−0.75	1.08	.73	0.0	NA	NA	NA	NA	NA
	Overall	0.15	−0.22	0.51	0.43	0.0	−0.76	−1.40	−0.11	0.02	25.8

[a]NA = interaction cannot be estimated because it is redundant. [b]Model 1: covariates in the meta-regression model alone. [c]Model 2/Group 1: covariate simultaneously with other Group 1 covariates in the meta-regression model. R^2 of the model including all covariates. Model 2/Group 2: covariate simultaneously with the Group 1 covariate "type of comparison group" in the meta-regression model. [d]R^2 (%): Negative pseudo R^2 values truncated to zero.

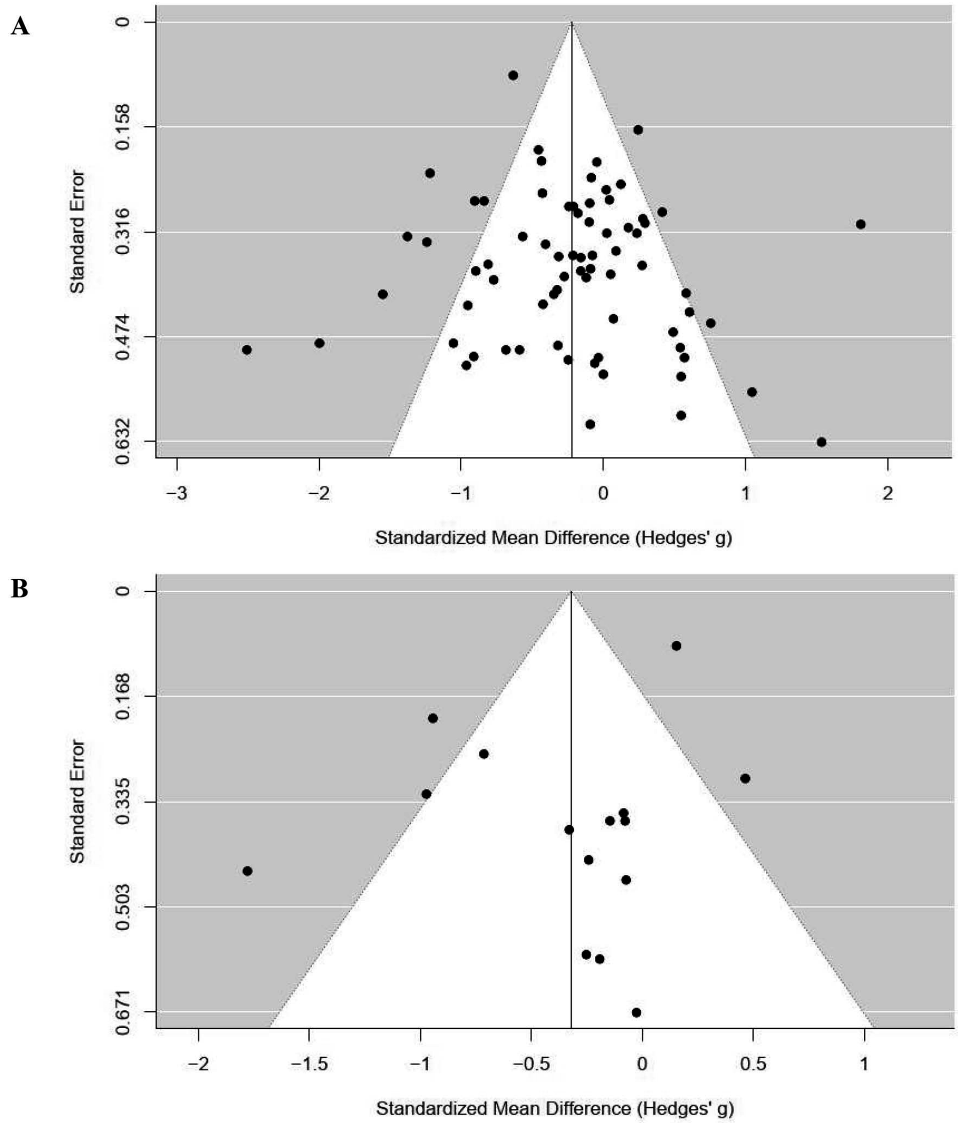

Figure 3. Funnel plots of studies included in the meta-analysis: (A) after intervention (n = 58) and (B) after follow-up period (n = 13).

$I^2 = 76.3\%$). No clear indication of asymmetry was found in the visual inspection of the funnel plot (Fig. 3) or in a statistical test for asymmetry ($P = .48$). In the meta-regression, a relationship between the exergaming effect and the type of comparison group was observed. The effect was small (SMD = 0.48, 95% CI = 0.20 to 0.77) when the type of the comparison group was evaluated alone, explaining 18.6% of the variance, and medium (SMD = 0.50, 95% CI = 0.19 to 0.81) when it was evaluated together with other covariates, explaining 14.1% of the variance (Tab. 1). Compared with the groups that had no exercise protocol (ie, inactive control), the relationship between the magnitude of the effectiveness of exergaming and covariate indicated moderate (SMD = −0.51, 95% CI = −0.74 to −0.28) benefit on walking improvements. In groups that had different exercising protocols (ie, active control), the benefit was minuscule (SMD = −0.03, 95% CI = −0.20 to 0.15).

After Follow-Up

Compared with active and inactive comparisons, exergaming was more or equally effective (SMD = −0.32, 95% CI = −0.64 to 0.00; 1028 participants, 13 studies; low-quality evidence) in enhancing walking (Fig. 2). Heterogeneity was substantial ($Q = 56.94$, $P < .0001$, $I^2 = 72.8\%$). Visual inspection of the funnel plot (Fig. 3) showed that the results by Lauzé et al[37] differ from those of other studies. A statistical test did not indicate asymmetry ($P = .95$).

Discussion

This systematic review and meta-analysis summarized the evidence from the effectiveness of exergame-based intervention on walking compared with those who had different exercising protocols or no exercise protocols among adults 60 years or older without neurological disorders. After the intervention period, the results demonstrated a small, significant effect for walking, favoring exergame interventions over comparisons. After a nonexergaming follow-up period, the results showed better effects on the exergame group. The type of comparison group (ie, inactive or active control) had the strongest association with the effect of exergaming, suggesting that compared with participants who did not exercise, participants who had exergame intervention received more benefits. Other covariates explored (participants' age or baseline walking performance, duration or intervention setting, number of sessions per week, session duration, technology used, and high risk of bias) indicated no impact on results. Methodologic quality assessment showed mostly a moderate risk of bias within studies. The high risk of bias did not have an impact on the magnitude of effectiveness. Certainty of evidence varied from moderate to low and substantial statistical heterogeneity was observed.

Prior research among older adults had studied the effectiveness of exergame-based interventions in patients with neurological disorders[16] by pooling outcomes measuring different characteristics of physical performance, such as muscle strength and gait[10] or balance and gait,[17] or with a variety of study designs.[18] To the best of our knowledge, this is the first systematic review and meta-analysis of RCTs to focus solely on study results on outcomes measuring walking after exergame-based interventions in older adults without neurological disorders. Additionally, we also assessed the maintenance of a long-term impact from those RCTs that had a follow-up period after intervention. Only 8 of the 66 studies included in the review were excluded from the quantitative synthesis, mainly because of the availability of numerical data or because study participants were involved in 2 studies that had been included in qualitative synthesis. As a result, outcome variables measuring walking were evaluated in the meta-analysis from 58 RCTs with 3102 participants, representing a sufficient number to assess the variance between studies.[38] Walking was comprehensively assessed from different perspectives (functional, speed, and distance), as it can be measured with several validated and standardized tests. To have a broad view of how exergaming is compared with other interventions, different comparisons (other exergame, other exercise with or without cognitive tasks, and no exercise) were included in the meta-analysis. In addition, in the meta-regression analysis, we were able to take into account different covariates, such as participants' walking performance at the baseline, although in studies, walking was measured with different tests. Furthermore, we included comprehensive information on exergame protocols and technologies used in the studies accepted in the review. This may help researchers and rehabilitation professionals evaluate the possibilities of exergame-based interventions.

The study characteristics of the included studies show that exergaming may be used to enhance walking in a wide variety of participants and settings, as has also been noted in earlier reviews.[12,13] Nearly one-half of the studies in our review did not focus on participants with risks or illnesses affecting their health. This may have been why the effect size remained small. A similar effect was also thought to be related to the study results of Howes et al[12] and Vázquez et al.[10] We are not able to fully compare our results with prior research, but there are some similarities that are good to highlight. Howes et al[12] investigated the effect of computer gaming on functional mobility. The results of 16 studies with 670 participants favored exergaming over active or inactive control, but the effect was not significant.[12] Comparing this result with our meta-analysis, the reason for the difference may be the large number of studies published after 2016 that we included in the analysis leading to estimates that are more extensive. Functional mobility was also assessed in the study of Donath et al,[17] who analyzed the effect separately in active and inactive control groups. As in our results, the type of control group affected their results; when an exergaming was compared with an inactive control, the effect suggested a benefit in the exergame group, but when an exergaming was compared with an active control, the effect suggested a benefit in the control group. Nevertheless, we are not able to fully compare the results because Donath et al[17] included Berg's balance test in the analysis. In our study, we excluded this outcome from the analysis because we considered it a measure of balance. Vázquez et al,[10] in turn, combined active and inactive control groups in the same manner as in our meta-analysis. They found that compared with comparison groups, the group with exergame-based interventions showed a significant positive effect on objectively measured and pooled outcomes measuring physical health. The results are consistent with the results of our study, but notably, their study combined a variety of outcomes measuring physical functioning, such as walking and muscle strength. Moreover, Vázquez et al[10] analyzed the moderating effect of several covariates such as age, which corresponds to the covariate studied in our study. The results are conflicting; Vázquez et al[10] found that older participants benefitted more from video game-based interventions than from comparisons. In our analysis, there was no relationship between the exergaming effect and age.

Strengths and Limitations

The certainty and quality of this systematic review and meta-analysis is increased by the protocol registration, comprehensive search strategy, accurately defined criteria to assess search results, use of 2 reviewers in decision making in eligibility and assessments, and analysis methods used in the meta-analysis and the meta-regression. Despite these strengths, the review had some limitations that are worth noting in the generalization of the results. In many studies included in the review, sample sizes were below 20 in the experimental or comparison group, and studies had variation in interventions, type of comparison group, and walking outcomes. These factors may make assessments of the impact and effect of covariates misleading. To correct these effects, a random effect model was used in the meta-analysis, and a novel and extensive multiple imputation model was used in the meta-regression. The majority of studies (84.7%) had some concerns in selective reporting. The reason for this was mainly due to the lack of prespecified reporting and analysis methods. Future RCTs should aim to register the study, to publish a protocol article when possible, and to enhance overall methodological rigor to lower the risk of bias. Assessment of funnel plots indicated the possibility of publication bias, but it is likely that the risk remained low because of the extensive search strategy used in the literature search.

Despite these limitations, the results of this systematic review and meta-analysis provide evidence of the benefits of using exergaming to enhance walking in older adults without neurological disorders. The results are based on comprehensive research findings, more than one-half of which have been published in the previous 3 years and confirm prior research findings of the effectiveness of exergame-based training. The results represent a positive advantage in enhancing walking when a novel exercise method is used in physical rehabilitation and indicate that compared with other types of exercise interventions, similar exercise effects may be achieved with exergame-based interventions. This finding indicates that to improve walking in this age group, physiotherapists and other rehabilitation professionals may consider gamified exercises in physical rehabilitation as a promising form of exercise. Furthermore, the findings indicate that the benefits of exergame-based training are maintained in the long term.

In conclusion, older adults without neurological disorders showed improvements in walking more with exergame-based training than with active or inactive protocols. Even greater benefits were observed when exergaming groups were compared with inactive comparison groups. In addition, the benefits of exergaming are maintained in the long term. However, the favorable effect of exergame-based interventions remained small, heterogeneity between studies were substantial, and there is no clear evidence if positive effects were associated with age, baseline walking performance, and technology or specific regimen used in the exergame protocol. To strengthen the evidence, more RCTs with lower methodological variance and higher quality are needed to compare the effectiveness between gamified intervention and interventions with different exercising protocols.

Author Contributions

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Funding

This research was funded by the Business Finland, SE Innovations Oy (Senior Some Oy), Suunto Oy, Physiotools Oy, GoodLife Technology Oy, Lingsoft Oy, eSeteli Palveluverkko Oy, PN Turku Oy, Ade Animations Design & Effects Oy, Adesante Oy, and Realmax Oy.

Systematic Review Registration

This systematic review was registered prospectively in PROSPERO (CRD42020148701).

Disclosures

The authors completed the ICMJE Form for Disclosure of Potential Conflicts of Interest and reported no conflicts of interest.

References

1. Pereira C, Baptista F, Cruz-Ferreira A. Role of physical activity, physical fitness, and chronic health conditions on the physical independence of community-dwelling older adults over a 5-year period. *Arch Gerontol Geriatr*. 2016;65:45–53.
2. Tsai LT, Rantakokko M, Rantanen T, Viljanen A, Kauppinen M, Portegijs E. Objectively measured physical activity and changes in life-space mobility among older people. *Journals Gerontol-Ser A Biol Sci Med Sci*. 2016;71:1466–1471.
3. Groessl EJ, Kaplan RM, Rejeski WJ, et al. Physical activity and performance impact long-term quality of life in older adults at risk for major mobility disability. *Am J Prev Med*. 2019;56:141–146.
4. Martinez-Gomez D, Bandinelli S, Del-Panta V, Talluri E, Guralnik JM, Ferrucci L. Three-year changes in physical activity and subsequent loss of ability to walk 400 m in older adults: the InCHIANTI study. *Am J Phys Med Rehabil*. 2018;97:212–215.
5. Pahor M, Guralnik JM, Ambrosius WT, et al. Effect of structured physical activity on prevention of major mobility disability in older adults: the LIFE study randomized clinical trial. *JAMA*. 2014;311: 2387–2396.
6. Department of Health & Human Services. Physical Activity Guidelines Advisory Committee. 2018. https://health.gov/paguidelines/second-edition/report/pdf/PAG_Advisory_Committee_Report.pdf.
7. Bouaziz W, Lang PO, Schmitt E, Kaltenbach G, Geny B, Vogel T. Health benefits of multicomponent training programmes in seniors: a systematic review. *Int J Clin Pract*. 2016;70:520–536.
8. Aartolahti E, Lönnroos E, Hartikainen S, Häkkinen A. Long-term strength and balance training in prevention of decline in muscle strength and mobility in older adults. *Aging Clin Exp Res*. 2020;32: 59–66.
9. Sardi L, Idri A, Fernández-Alemán JL. A systematic review of gamification in e-health. *J Biomed Inform*. 2017;71:31–48.
10. Vázquez FL, Otero P, García-Casal JA, Blanco V, Torres ÁJ, Arrojo M. Efficacy of video game-based interventions for active aging: a systematic literature review and meta-analysis. *PLoS One*. 2018;13:1–24.
11. Skjæret N, Nawaz A, Morat T, Schoene D, Helbostad JL, Vereijken B. Exercise and rehabilitation delivered through exergames in older adults: an integrative review of technologies, safety and efficacy. *Int J Med Inform*. 2016;85:1–16.
12. Howes SC, Charles DK, Marley J, Pedlow K, McDonough SM. Gaming for health: systematic review and meta-analysis of the physical and cognitive effects of active computer gaming in older adults. *Phys Ther*. 2017;97:1122–1137.
13. Ravenek KE, Wolfe DL, Hitzig SL. A scoping review of video gaming in rehabilitation. *Disabil Rehabil Assist Technol*. 2016;11: 445–453.
14. Cacciata M, Stromberg A, Lee JA, et al. Effect of exergaming on health-related quality of life in older adults: a systematic review. *Int J Nurs Stud*. 2019;93:30–40.
15. Choi SD, Guo L, Kang D, Xiong S. Exergame technology and interactive interventions for elderly fall prevention: a systematic literature review. *Appl Ergon*. 2017;65:570–581.

16. Cano Porras D, Siemonsma P, Inzelberg R, Zeilig G, Plotnik M. Advantages of virtual reality in the rehabilitation of balance and gait: systematic review. *Neurology*. 2018;90: 1017–1025.
17. Donath L, Rössler R, Faude O. Effects of virtual reality training (exergaming) compared to alternative exercise training and passive control on standing balance and functional mobility in healthy community-dwelling seniors: a meta-analytical review. *Sports Med*. 2016;46:1293–1309.
18. Reis E, Postolache G, Teixeira L, Arriaga P, Lima ML, Postolache O. Exergames for motor rehabilitation in older adults: an umbrella review. *Phys Ther Rev*. 2019;24:84–99.
19. Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med*. 2009;6: e1000097.
20. Scottish Intercollegiate Guidelines Network (SIGN). Search filters. 2018. Accessed December 15, 2018. https://www.sign.ac.uk/search-filters
21. University of Alberta. Search filters. 2018. Accessed December 15, 2018. https://guides.library.ualberta.ca/c.php?g=248586&p=1655962
22. Veritas Health Innovation. Covidence systematic review software. 2020. https://www.covidence.org/
23. Higgins JPT, Savović J, Page MJ, Sterne JAC. *Revised Cochrane risk-of-bias tool for randomized trials (RoB 2)*. ROB2 Development Group. 2019. Accessed June 24, 2020. https://sites.google.com/site/riskofbiastool/welcome/rob-2-0-tool/current-version-of-rob-2
24. R Core Team. R: *A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. 2013. Accessed December 3, 2020. https://www.r-project.org/
25. Viechtbauer W. Conducting meta-analyses in R with the metafor. *J Stat Softw*. 2010;36:1–48.
26. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hillsdale, NJ, USA: Lawrence Erlbaum; 1988.
27. Higgins J, Li T, Deeks J. Chapter 6: Choosing effect measures and computing estimates of effect. *Cochrane Handbook for Systematic Reviews of Interventions Version 6.0* 2019. Accessed June 24, 2020. www.training.cochrane.org/handbook.
28. Gleser LJ, Olkin I. Stochastically dependent effect sizes. In: Cooper H, Hedges LV, Valentine JC, eds., *The Handbook of Research Synthesis and Meta-Analysis*. 2nd ed. New York, NY, USA: Russell Sage Foundation; 2009: 357–376.
29. Schünemann H, Brożek J, Guyatt G, Oxman A. GRADE handbook for grading quality of evidence and strength of recommendations. Updated October 2013. *The GRADE Working Group*. 2013. Accessed June 24, 2020. https://training.cochrane.org/resource/grade-handbook
30. Sterne JAC, Sutton AJ, Ioannidis JPA, et al. Recommendations for examining and interpreting funnel plot asymmetry in meta-analyses of randomised controlled trials. *BMJ*. 2011;343: 1–8.
31. Raudenbush SW. Analyzing effect sizes: Random effects models. In: Cooper H, Hedges LV, Valentine JC, eds., *The Handbook of Research Synthesis and Meta-Analysis*. 2nd ed. New York, NY, USA: Russell Sage Foundation; 2009: 295–315.
32. van Buuren S. *Flexible Imputation of Missing Data*. Boca Raton, FL, USA: CRC Press; 2018.
33. van Buuren S, Groothuis-Oudshoorn K. Mice: multivariate imputation by chained equations in R. *J Stat Softw*. 2011;45:1–67.
34. Santamaría KG, Fonseca AS, Jiménez JM, Mora LCS. Balance, attention and concentration improvements following an exergame training program in elderly. *Retos-Nuevas Tendencias En Educ Fis Deport Y Recreacion*. 2018;2041: 102–105.
35. Schoene D, Lord SR, Delbaere K, Severino C, Davies TA, Smith ST. A randomized controlled pilot study of home-based step training in older people using videogame technology. *PLoS One*. 2013;8:e57734–e57734.
36. Uzor S, Baillie L. Recov-R: evaluation of a home-based tailored exergame system to reduce fall risk in seniors. *Acm Trans Comput Interact*. 2019;26:1–38.
37. Lauzé M, Martel D, Aubertin-Leheudre M. Feasibility and effects of a physical activity program using gerontechnology in assisted living communities for older adults. *J Am Med Dir Assoc*. 2017;18: 1069–1075.
38. Valentine JC, Pigott TD, Rothstein HR. How many studies do you need? A primer on statistical power for meta-analysis. *J Educ Behav Stat*. 2010;35:215–247.

SUPLEMENTARY MATERIAL A: METHODS

In the supplementary material A are

- full electronic search strategy that was done to the MEDLINE (Ovid) database for the literature search (table A1).
- study, participant, intervention and outcome information extracted from the studies included in the review (table A2).
- obtained and confirmed data from original studies (table A3).
- conversion of given results to the mean and SD values (table A4).
- the priority list that defines the order of outcome variables measuring walking for synthesis of the results (table A5).

Table A1. The search strategy in the MEDLINE (Ovid) database.

#	Searches	Results 14.1.2019	Results 10.1.2020
1	Video Games/	4534	5104
2	Virtual Reality/	613	1426
3	Virtual Reality Exposure Therapy/	448	551
4	virtual reality.mp.	8278	9851
5	augmented reality.mp.	1396	1800
6	mixed reality.mp.	191	273
7	User-Computer Interface/	35191	36463
8	game technolog*.mp.	44	46
9	gamificati*.mp.	331	481
10	gamified.mp.	126	187
11	exergam*.mp.	496	612
12	computer gam*.mp.	1228	1323
13	wearable computing.mp.	71	84
14	digital rehabilitation.mp.	8	12
15	Wii*.mp.	949	1026
16	Sony Move*.mp.	1	1
17	Xbox*.mp.	156	176
18	X-box*.mp.	1762	1945
19	Playstation*.mp.	77	79
20	Kinect*.mp.	1006	1156
21	Intel Realsense*.mp.	3	8
22	webcam technology.mp.	3	3
23	motion detection.mp.	1262	1355
24	Motion sensor gam*.mp.	1	1
25	motion-controlled gam*.mp.	5	6
26	1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24 or 25	50089	54183
27	Rehabilitation/ or exp Exercise Therapy/	62230	66343
28	therapeutic exercise.mp.	910	983
29	exp Physical Therapy Modalities/	140502	148700
30	exp Exercise/	173602	187759
31	physical rehabilitation.mp.	1689	1858
32	physiotherap*.mp.	23401	25339
33	physical therap*.mp.	50567	53497
34	27 or 28 or 29 or 30 or 31 or 32 or 33	337782	360238
35	Randomized Controlled Trials as Topic/	120416	129932
36	randomized controlled trial/	474451	498448
37	Random Allocation/	97207	101853
38	Double-Blind Method/	149037	155671
39	Single Blind Method/	26115	27955
40	clinical trial/	514077	520737
41	clinical trial, phase i.pt.	18563	19850
42	clinical trial, phase ii.pt.	29941	31917
43	clinical trial, phase iii.pt.	14503	16174
44	clinical trial, phase iv.pt.	1632	1818
45	controlled clinical trial.pt.	92865	93516
46	randomized controlled trial.pt.	474451	498448
47	multicenter study.pt.	243805	264599
48	clinical trial.pt.	514077	520737
49	exp Clinical Trials as topic/	320731	335578
50	35 or 36 or 37 or 38 or 39 or 40 or 41 or 42 or 43 or 44 or 45 or 46 or 47 or 48 or 49	1271424	1338136
51	(clinical adj trial$).tw.	323540	351381
52	((singl$ or doubl$ or treb$ or tripl$) adj (blind$3 or mask$3)).tw.	161134	168770
53	PLACEBOS/	34190	34687
54	placebo$.tw.	201037	210823
55	randomly allocated.tw.	25520	27572
56	(allocated adj2 random$).tw.	28631	30811
57	51 or 52 or 53 or 54 or 55 or 56 or 57	576243	615001
58	50 or 57	1506846	1593063
59	case report.tw.	282087	300339
60	letter/	1012544	1058044
61	historical article/	349577	356143
62	59 or 60 or 61	1629568	1699138
63	58 not 62	1472735	1557049
64	26 and 34 and 63	673	765
			51

Table A2. Study, participant, intervention and outcome information extracted from the studies included in the review.

Domain	Extracted data
Study Identification	Country, sources of funding and author information
Methods	Study design and aim of the study
Population	Inclusion and exclusion criteria, group differences, characteristics' of participant as described in the studies
Interventions	Description of the interventions in experimental and comparison groups: duration, setting, type of training, used technology, guidance, exercise program (sessions in week, session time, session description, progression), adherence, follow-up procedure, additional information that review author wanted to highlight
Outcomes	Outcomes measuring walking measured at baseline, after intervention and when available, after follow-up period (name, type, unit of measurement, measured values, number of participants analyzed, direction (lower/upper is better), data value (endpoint/change from baseline)
	Main results of outcomes measuring walking

Table A3. Information requested from original studies (n=18) and actions made.

Study	Reason for request	Response	Actions
Chow & Mann 2015 [1]	TUG change from baseline results reported (t test)	Endpoint Mean and SD values received via email	Endpoint values added to data extraction
Fung et al. 2012[2]	2MWT results reported as change% from baseline	Numerical data not received	Study excluded from meta-analysis
Htut et al. 2018 [3]	TUG results presented graphically	Endpoint Mean and SD values received via email.	Endpoint values added to data extraction
Khushnood et al. 2019 [4]	Participants' ages not reported	Mean age of participants under 60 years of old (information received via email)	Study excluded from the review (Reason: Wrong population)
Lauzé et al. 2017 [5]	TUG and Walking Speed results reported as change from baseline	Endpoint Mean and SD values not received	Change values are used in meta-analysis (the groups did not differ at basline)
Liao, Chen, & Wang 2019 [6]**; Liao, Chen, Lin, et al. 2019** [7]	Participants might be same in studies	Requested information not received	Liao et al. 2019 excluded from meta-analysis (Reason: Participant definition in trial registration)
Lin et al. 2007 [8]	Comparison of pre- and post-intervention values for Walking Speed on four different terrains perented graphically	Numerical data not received	Study excluded from meta-analysis
Maillot et al. 2012 [9]	TUG and 6MWT results reported as change from baseline	Endpoint Mean and SD values received via email.	Endpoint values added to data extraction
Mirelman et al. 2016 [10]	Study participants were from three cohorts, one of which included participants with neurological disorder.	2MWT results received by three cohorts.	Two cohorts, which matched review's inclusion criteria, added to meta-analysis
Monteiro-Junior et al. 2017 [11]	TUG and Walking speed results reported as change from baseline	Endpoint Mean and SD values received via email.	Endpoint values added to data extraction
Ray et al. 2012 [12]	Baseline characteristics information by groups not reportes	Participant data not received	Information remains missing from narrative synthesis
Sajid et al. 2016 [13]	6MWT results not reported	Results are not available to studies past 8 years (Information received via email)	Study excluded from meta-analysis
Santamaría et al. 2018 [14]	TUG results reported as p-values	Endpoint Mean and SD values received via email.	Endpoint values added to data extraction
Smaerup et al. 2015 [15]	DGI results reported as change from baseline	Endpoint Mean and SD values not received	Change values are used in meta-analysis (the groups did not differ at baseline)

Szturm et al. 2011 [16]	TUG results reported as change from basline, Walking Speed results presented graphically	Endpoint Mean and SD values received via email	Endpoint values added to data extraction
Tollar et al. 2019 [17]	6MWT and DGI post-intervention values not reported	Endpoint Mean and SD values received via email	Endpoint values added to data extraction
Uzor & Baillie 2019 [18]	Walking speed results presented graphically	Endpoint Mean and SD values received via email.	Endpoint values added to data extraction

Table A4. Calculation of the mean and standard deviation (SD) values in RCTs (n=7).

Study	Reported outcomes	Values calculated	Method
Bieryla & Dold 2013 [19]	median, lower IQR, upper IQR	mean, SD	Recommendation {q1, m, q3; n} [20]
Bieryla 2016 [21]	median, lower IQR, upper IQR	mean, SD	Recommendation {q1, m, q3; n}[20]
Eggenberger et al. 2015 [22]	mean, SE	SD	SD=SE*√N
Pichierri et al. 2012 [23]	median, lower IQR, upper IQR	mean, SD	Recommendation {q1, m, q3; n}[20]
Rendon et al. 2012 [24]	median, min, max	mean, SD	Recommendation {a, m, b; n}[20]
Schättin et al. 2016 [25]	median, lower IQR, upper IQR	mean, SD	Recommendation {q1, m, q3; n}[20]
Smaerup et al. 2015 [15]	mean, lower CI, upper CI	SD	SD=√N*(upper CI-lower CI)/2*tinv

Table A5. The priority list of outcome variables measuring walking in the studies included in the review.

#	Measurement	Unit of result	Direction	Incidence	Validity	Reliability	References
1	Timed "Up & Go" *) (e.g. TUG, 8ftUG, iTUG)	second	↓	40	2-3/3	Test-retest: 4/4 Inter-rater: 4/4 Intra-rater: 4/4	[26–29]
2	Walking speed*) (e.g. 4-m test, 10-m test, GAITRite)	milli-second, second, minute	↑	23	3/3 Normal pace ↑	Test-retest: 3-4/4 Inter-rater: 4/4	[27,29–33]
3	2MWT, 6MWT	feet, yard, meter	↑	16	3/3	Test-retest: 4/4 Inter-rater: 4/4	[29,34–36]
4	Functional Gait Assessment, Dynamic Gait Index, Tinetti Gait	score	↑	9	2-3/3	Test-retest: 4/4 Inter-rater: 3/4 Intra-rater: 3/4	[27,37–41]

Validity: 1/3 = small [r<.03], 2/3 = medium [r=.03-.05], 3/3 = large [r>.05] [42]
Reliability: 1/4 = poor [ICC<.05], 2/4 = moderate [ICC=.5-.75], 3/4 = good [ICC=.75-.9], 4/4 = excellent [ICC>.90] [43]
*) Single-task

REFERENCES

1. Chow DHK, Mann SKF. Effect of cyber-golfing on balance amongst the elderly in Hong Kong: A pilot randomised trial. *Hong Kong J Occup Ther*. 2015;26:9-13. doi:10.1016/j.hkjot.2015.08.001

2. Fung V, Ho A, Shaffer J, Chung E, Gomez M. Use of Nintendo Wii FitTM in the rehabilitation of outpatients following total knee replacement: A preliminary randomised controlled trial. *Physiotherapy*. 2012;98:183-188. doi:10.1016/j.physio.2012.04.001

3. Htut TZC, Hiengkaew V, Jalayondeja C, Vongsirinavarat M. Effects of physical, virtual reality-based, and brain exercise on physical, cognition, and preference in older persons: A randomized controlled trial. *Eur Rev Aging Phys Act*. 2018;15:1-12. doi:10.1186/s11556-018-0199-5

4. Khushnood K, Sultan N, Mehmood R, Qureshi S, Tariq H, Amjad I. Does Wii Fit balance training improve balance and reduce fall risk in diabetic patients as compared to balance training exercises? *Rawal Med J*. 2019;44:44-48.

5. Lauzé M, Martel D, Aubertin-Leheudre M. Feasibility and effects of a physical activity program using gerontechnology in assisted living communities for Older Adults. *J Am Med Dir Assoc*. 2017;18:1069-1075. doi:10.1016/j.jamda.2017.06.030

6. Liao, Y. Y.; Chen, I. H.; Wang RY. Effects of Kinect-based exergaming on frailty status and physical performance in prefrail and frail elderly: A randomized controlled trial. *Sci Rep*. 2019;9.

7. Liao Y-Y, Chen I-H, Lin Y-J, Chen Y, Hsu W-C. Effects of virtual reality-based physical and cognitive training on executive function and dual-task gait performance in

older adults with mild cognitive impairment: A randomized control trial. *Front Aging Neurosci*. 2019;11:1-10. doi:10.3389/fnagi.2019.00162

8. Lin DH, Lin YF, Chai HM, Han YC, Jan MH. Comparison of proprioceptive functions between computerized proprioception facilitation exercise and closed kinetic chain exercise in patients with knee osteoarthritis. *Clin Rheumatol*. 2007;26:520-528. doi:10.1007/s10067-006-0324-0

9. Maillot P, Perrot A, Hartley A. Effects of interactive physical-activity video-game training on physical and cognitive function in older adults. *Psychol Aging*. 2012;27:589-600. doi:10.1037/a0026268

10. Mirelman A, Rochester L, Maidan I, et al. Addition of a non-immersive virtual reality component to treadmill training to reduce fall risk in older adults (V-TIME): A randomised controlled trial. *Lancet*. 2016;388:1170-1182. doi:10.1016/S0140-6736(16)31325-3

11. Monteiro-Junior RS, Figueiredo LFDS, Maciel-Pinheiro PDT, et al. Virtual reality–based physical exercise with exergames (PhysEx) improves mental and physical health of institutionalized older adults. *J Am Med Dir Assoc*. 2017;18:454.e1-454.e9. doi:10.1016/j.jamda.2017.01.001

12. Ray C, Melton F, Ramirez R, Keller D. The effects of a 15-week exercise intervention on fitness and postural control in older adults. *Act Adapt Aging*. 2012;36:227-241. doi:10.1080/01924788.2012.696236

13. Sajid S, Dale W, Mustian K, et al. Novel physical activity interventions for older patients with prostate cancer on hormone therapy: A pilot randomized study. *J Geriatr Oncol*. 2016;7:71-80. doi:10.1016/j.jgo.2016.02.002

14. Santamaría KG, Fonseca AS, Jiménez JM, Mora LCS. Balance, attention and concentration improvements following an exergame training program in elderly. *Retos-Nuevas Tendencias En Educ Fis Deport Y Recreacion*. 2018;2041:102-105.

15. Smaerup M, Grönvall E, Larsen SB, Laessoe U, Henriksen J-J, Damsgaard EM. Computer-assisted training as a complement in rehabilitation of patients with chronic vestibular dizziness: A randomized controlled trial. *Arch Phys Med Rehabil*. 2015;96:395-401. doi:10.1016/j.apmr.2014.10.005

16. Szturm T, Betker AL, Moussavi Z, Desai A, Goodman V. Effects of an interactive computer game exercise regimen on balance impairment in frail community-dwelling older adults: A randomized controlled trial. *Phys Ther*. 2011;91:1449-1462. doi:10.2522/ptj.20090205

17. Tollar J, Nagy F, Moizs M, Toth BE, Sanders LMJ, Hortobagyi T. Diverse exercises similarly reduce older adults' mobility limitations. *Med Sci Sports Exerc*. 2019;51:1809-1816. doi:10.1249/MSS.0000000000002001

18. Uzor S, Baillie L. Recov-R: Evaluation of a home-based tailored exergame system to reduce fall risk in seniors. *Acm Trans Comput Interact*. 2019;26. doi:10.1145/3325280

19. Bieryla KA, Dold NM. Feasibility of Wii Fit training to improve clinical measures of balance in older adults. *Clin Interv Aging*. 2013;8:775-781. doi:10.2147/CIA.S46164

20. Wan X, Wang W, Liu J, Tong T. Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range. *BMC Med Res Methodol*. 2014;14:1-13. doi:10.1186/1471-2288-14-135

21. Bieryla KA. Xbox Kinect training to improve clinical measures of balance in older adults: A pilot study. *Aging Clin Exp Res*. 2016;28:451-457. doi:10.1007/s40520-015-

0452-y

22. Eggenberger P, Theill N, Holenstein S, Schumacher V, de Bruin ED. Multicomponent physical exercise with simultaneous cognitive training to enhance dual-task walking of older adults: A secondary analysis of a 6-month randomized controlled trial with I-year follow-up. *Clin Interv Aging*. 2015;10:1711-1732. doi:10.2147/CIA.S91997

23. Pichierri G, Murer K, de Bruin ED. A cognitive-motor intervention using a dance video game to enhance foot placement accuracy and gait under dual task conditions in older adults: A randomized controlled trial. *BMC Geriatr*. 2012;12:74. doi:10.1186/1471-2318-12-74

24. Rendon AA, Lohman EB, Thorpe D, Johnson EG, Medina E, Bradley B. The effect of virtual reality gaming on dynamic balance in older adults. *Age Ageing*. 2012;41:549-552. doi:10.1093/ageing/afs053

25. Schättin A, Arner R, Gennaro F, de Bruin ED. Adaptations of prefrontal brain activity, executive functions, and gait in healthy elderly following exergame and balance training: A randomized-controlled study. *Front Aging Neurosci*. 2016;8. doi:10.3389/fnagi.2016.00278

26. Christopher A, Kraft E, Olenick H, Kiesling R, Doty A. The reliability and validity of the Timed Up and Go as a clinical tool in individuals with and without disabilities across a lifespan: a systematic review: Psychometric properties of the Timed Up and Go. *Disabil Rehabil*. Published online 2019. doi:10.1080/09638288.2019.1682066

27. van Iersel MB, Munneke M, Esselink RAJ, Benraad CEM, Olde Rikkert MGM. Gait velocity and the Timed-Up-and-Go test were sensitive to changes in mobility in frail elderly patients. *J Clin Epidemiol*. 2008;61:186-191. doi:10.1016/j.jclinepi.2007.04.016

28. Rydwik E, Bergland A, Forsén L, Frändin K. Psychometric properties of Timed Up and Go in elderly people: A systematic review. *Phys Occup Ther Geriatr*. 2011;29:102-125. doi:10.3109/02703181.2011.564725

29. Steffen TM, Hacker TA, Mollinger L. Age- and gender-related test performance in community-dwelling elderly people:Six-minute Walk Test, Berg Balance Scale , Timed Up & Go Test, and Gait Speed. *Phys Ther*. 2002;82:128-137.

30. Bilney B, Morris M, Webster K. Concurrent related validity of the GAITRite walkway system for quantification of the spatial and temporal parameters of gait. *Gait Posture*. 2003;17:68-74. doi:10.1016/S0966-6362(02)00053-X

31. Kim H, Park I, Lee H joo, Lee O. The reliability and validity of gait speed with different walking pace and distances against general health, physical function, and chronic disease in aged adults. *J Exerc Nutr Biochem*. 2016;20:46-50. doi:10.20463/jenb.2016.09.20.3.7

32. Peters DM, Fritz SL, Krotish DE. Assessing the reliability and validity of a shorter walk test compared with the 10-Meter Walk Test for measurements of gait speed in healthy, older adults. *J Geriatr Phys Ther*. 2013;36:24-30. doi:10.1519/JPT.0b013e318248e20d

33. Rydwik E, Bergland A, Forsén L, Frändin K. Investigation into the reliability and validity of the measurement of elderly people's clinical walking speed: A systematic review. *Physiother Theory Pract*. 2012;28:238-256. doi:10.3109/09593985.2011.601804

34. Bean JF, Kiely DK, Leveille SG, et al. The 6-minute walk test in mobility-limited elders: What is being measured? *Journals Gerontol - Ser A Biol Sci Med Sci*. 2002;57. doi:10.1093/gerona/57.11.M751

35. Chan WLS, Pin TW. Reliability, validity and minimal detectable change of 2-minute

walk test, 6-minute walk test and 10-meter walk test in frail older adults with dementia. *Exp Gerontol*. 2019;115:9-18. doi:10.1016/j.exger.2018.11.001

36. Connelly DM, Thomas BK, Cliffe SJ, Perry WM, Smith RE. Clinical utility of the 2-minute walk test for older adults living in long-term care. *Physiother Canada*. 2009;61:78-87. doi:10.3138/physio.61.2.78

37. Parveen H, Noohu MM. Evaluation of psychometric properties of Tinetti performance-oriented mobility assessment scale in subjects with knee osteoarthritis. *Hong Kong Physiother J*. 2017;36:25-32. doi:10.1016/j.hkpj.2016.07.001

38. Whitney S, Wrisley D, Furman J. Concurrent validity of the Berg Balance Scale and the Dynamic Gait Index in people with vestibular dysfunction. *Physiother Res Int*. 2003;8:178-186. doi:10.1002/pri.288

39. Wrisley DM, Walker ML, Echternach JL, Strasnick B. Reliability of the Dynamic Gait Index in people with vestibular disorders. *Arch Phys Med Rehabil*. 2003;84:1528-1533. doi:10.1016/S0003-9993(03)00274-0

40. Wrisley DM, Marchetti GF, Kuharsky DK, Whitney SL. Reliability, internal consistency, and validity of data obtained with the functional gait assessment. *Phys Ther*. 2004;84:906-918. doi:10.1093/ptj/84.10.906

41. Wrisley DM, Kumar N. Functional Gait Assessment : Concurrent, discriminative, and predictive validity in community dwelling older adults. *Phys Ther*. 2010;90:1-13. doi:10.2522/ptj.20090069

42. Cohen J. A Power Primer. *Quant methods Psychol*. 1992;112:155-159. doi:10.1037/0033-2909.112.1.155

43. Koo TK, Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J Chiropr Med*. 2016;15:155-163. doi:10.1016/j.jcm.2016.02.012

SUPLEMENTARY MATERIAL B: REFERENCES

In this supplementary material B are

- references of the studies that were included (n=66) in the review (table B1).
- references of the studies that did not met the inclusion criteria and were excluded (n=152) in the full text screening (table B2).

Table B1. Included studies (n=66) with justification for exclusion from the meta-analysis after the intervention (n=8) and after the follow-up period (n=2).

Studies included in the review	Reason for exclusion from the meta-analysis
Bacha J, Gomes G, De Freitas T, et al. Effects of kinect adventures games versus conventional physical therapy on postural control in elderly people: A randomized controlled trial. *Games Health J*. 2018;7:24-36. doi:10.1089/g4h.2017.0065	
Bieryla KA. Xbox Kinect training to improve clinical measures of balance in older adults: A pilot study. *Aging Clin Exp Res*. 2016;28:451-457. doi:10.1007/s40520-015-0452-y	
Bieryla KA, Dold NM. Feasibility of Wii Fit training to improve clinical measures of balance in older adults. *Clin Interv Aging*. 2013;8:775-781. doi:10.2147/CIA.S46164	
Chow DHK, Mann SKF. Effect of cyber-golfing on balance amongst the elderly in Hong Kong: A pilot randomised trial. *Hong Kong J Occup Ther*. 2015;26:9-13. doi:10.1016/j.hkjot.2015.08.001	
Christiansen CL, Bade MJ, Davidson BS, Dayton MR, Stevens-Lapsley JE. Effects of weight-bearing biofeedback training on functional movement patterns following total knee arthroplasty: A randomized controlled trial. *J Orthop Sports Phys Ther*. 2015;45:647-655. doi:10.2519/jospt.2015.5593	
Daniel K. Wii-hab for pre-frail older adults. *Rehabil Nurs*. 2012;37:195-201. doi:10.1002/rnj.25	
Delbroek T, Vermeylen W, Spildooren J. The effect of cognitive-motor dual task training with the biorescue force platform on cognition, balance and dual task performance in institutionalized older adults: a randomized controlled trial. *J Phys Ther Sci*. 2017;29:1137-1143. doi: 10.1589/jpts.29.1137	
Eggenberger P, Theill N, Holenstein S, Schumacher V, de Bruin ED. Multicomponent physical exercise with simultaneous cognitive training to enhance dual-task walking of older adults: A secondary analysis of a 6-month randomized controlled trial with I-year follow-up. *Clin Interv Aging*. 2015;10:1711-1732. doi:10.2147/CIA.S91997	
Fung V, Ho A, Shaffer J, Chung E, Gomez M. Use of Nintendo Wii FitTM in the rehabilitation of outpatients following total knee replacement: A preliminary randomised controlled trial. *Physiotherapy*. 2012;98:183-188. doi:10.1016/j.physio.2012.04.001	Post Intervention: Numerical data not available
Gomes GCV, Simoes M do S, Lin SM, et al. Feasibility, safety, acceptability, and functional outcomes of playing Nintendo Wii Fit PlusTM for frail older adults: A randomized feasibility clinical trial. *Maturitas*. 2018;118:20-28. doi:10.1016/j.maturitas.2018.10.002	
Gschwind YJ, Eichberg S, Ejupi A, et al. ICT-based system to predict and prevent falls (iStoppFalls): Results from an international multicenter randomized controlled trial. *Eur Rev Aging Phys Act*. 2015;12:1-11. doi:10.1186/s11556-015-0155-6	Post Follow-up: walking outcomes were not measured
Htut TZC, Hiengkaew V, Jalayondeja C, Vongsirinavarat M. Effects of physical, virtual reality-based, and brain exercise on physical, cognition, and preference in older persons: A randomized controlled trial. *Eur Rev Aging Phys Act*. 2018;15:1-12. doi:10.1186/s11556-018-0199-5	
Hughes TF, Flatt JD, Fu B, Butters MA, Chang CCH, Ganguli M. Interactive video gaming compared with health education in older adults with mild cognitive impairment: A feasibility study. *Int J Geriatr Psychiatry*. 2014;29:890-898. doi:10.1002/gps.4075	
Imam B, Miller WC, Finlayson H, Eng JJ, Jarus T. A randomized controlled trial to evaluate the feasibility of the Wii Fit for improving walking in older adults with lower limb amputation. *Clin Rehabil*. 2017;31:82-92.	

doi:10.1177/0269215515623601	
Jorgensen MG, Laessoe U, Hendriksen C, Nielsen OBF, Aagaard P. Efficacy of nintendo wii training on mechanical leg muscle function and postural balance in community-dwelling older adults: A randomized controlled trial. *Journals Gerontol - Ser A Biol Sci Med Sci*. 2013;68:845-852. doi:10.1093/gerona/gls222	
Jung D-I, Ko D-S, Jeong M-A. Kinematic effect of Nintendo Wii^{TM} sports program exercise on obstacle gait in elderly women with falling risk. *J Phys Ther Sci*. 2015;27:1397-1400. doi:10.1589/jpts.27.1397	
Karahan AY, Tok F, Taşkın H, Küçüksaraç S, Başaran A, Yildirim P. Effects of exergames on balance, functional mobility, and quality of life of geriatrics versus home exercise programme: Randomized controlled study. *Cent Eur J Public Health*. 2015;23:S14-S18. doi:10.21101/cejph.a4081	
Ku J, Kim YJ, Cho S, Lim T, Lee HS, Kang YJ. Three-dimensional augmented reality system for balance and mobility rehabilitation in the elderly: A randomized controlled trial. *Cyberpsychology, Behav Soc Netw*. 2019;22:132-141. doi:10.1089/cyber.2018.0261	
Kwok BC, Pua YH. Effects of Wii Active exercises on fear of falling and functional outcomes in community-dwelling older adults: a randomised control trial. *Age Ageing*. 2016;45:621-628. doi:10.1093/ageing/afw108	
Lauzé M, Martel D, Agnoux A, et al. Feasibility, acceptability and effects of a home-based exercise program using a gerontechnology on physical capacities after a minor injury in community-living older adults: A pilot study. *J Nutr Heal Aging*. 2018;22:16-25. doi:10.1007/s12603-017-0938-8	
Lauzé M, Martel D, Aubertin-Leheudre M. Feasibility and effects of a physical activity program using gerontechnology in assisted living communities for Older Adults. *J Am Med Dir Assoc*. 2017;18:1069-1075. doi:10.1016/j.jamda.2017.06.030	
Laver K, George S, Ratcliffe J, et al. Use of an interactive video gaming program compared with conventional physiotherapy for hospitalised older adults: A feasibility trial. *Disabil Rehabil*. 2012;34:1802-1808. doi:10.3109/09638288.2012.662570	
Lee M, Son J, Kim J, Yoon BC. Individualized feedback-based virtual reality exercise improves older women's self-perceived health: A randomized controlled trial. *Arch Gerontol Geriatr*. 2015;61:154-160. doi:10.1016/j.archger.2015.06.010	
Lee S, Shin S. Effectiveness of virtual reality using video gaming technology in elderly adults with diabetes mellitus. *Diabetes Technol Ther*. 2013;15:489-496. doi:10.1089/dia.2013.0050	
Lee Y, Choi W, Lee K, Song C, Lee S. Virtual reality training with three-dimensional video games improves postural balance and lower extremity strength in community-dwelling older adults. *J Aging Phys Act*. 2017;25:621-627. doi:10.1123/japa.2015-0271	
Liao Y-Y, Chen I-H, Lin Y-J, Chen Y, Hsu W-C. Effects of virtual reality-based physical and cognitive training on executive function and dual-task gait performance in older adults with mild cognitive impairment: A randomized control trial. *Front Aging Neurosci*. 2019;11:1-10. doi:10.3389/fnagi.2019.00162	Post Intervention: Same participants as in Liao, Chen & Wang 2019
Liao Y-Y, Chen I-H, Wang R-Y. Effects of Kinect-based exergaming on frailty status and physical performance in prefrail and frail elderly: A randomized controlled trial. *Sci Rep*. 2019;9:1-9. doi:10.1038/s41598-019-45767-y	
Lim J, Cho JJ, Kim J, Kim Y, Yoon BC. Design of virtual reality training program for prevention of falling in the elderly: A pilot study on complex versus balance exercises. *Eur J Integr Med*. 2017;15:64-67. doi:10.1016/j.eujim.2017.09.008	

Lin DH, Lin YF, Chai HM, Han YC, Jan MH. Comparison of proprioceptive functions between computerized proprioception facilitation exercise and closed kinetic chain exercise in patients with knee osteoarthritis. *Clin Rheumatol*. 2007;26:520-528. doi:10.1007/s10067-006-0324-0	Post Intervention: Numerical data not available
Maillot P, Perrot A, Hartley A. Effects of interactive physical-activity video-game training on physical and cognitive function in older adults. *Psychol Aging*. 2012;27:589-600. doi:10.1037/a0026268	
Maillot P, Perrot A, Hartley A, Do MC. The braking force in walking: Age-related differences and improvement in older adults with exergame training. *J Aging Phys Act*. 2014;22:518-526. doi:10.1123/JAPA.2013-0001	Post intervention: Same participants as in Maillot et al. 2012
Martel D, Lauzé M, Agnoux A, et al. Comparing the effects of a home-based exercise program using a gerontechnology to a community-based group exercise program on functional capacities in older adults after a minor injury. *Exp Gerontol*. 2018;108:41-47. doi:10.1016/j.exger.2018.03.016	
Micarelli A, Viziano A, Micarelli B, Augimeri I, Alessandrini M. Vestibular rehabilitation in older adults with and without mild cognitive impairment: Effects of virtual reality using a head-mounted display. *Arch Gerontol Geriatr*. 2019;83:246-256. doi:10.1016/j.archger.2019.05.008	
Mirelman A, Rochester L, Maidan I, et al. Addition of a non-immersive virtual reality component to treadmill training to reduce fall risk in older adults (V-TIME): A randomised controlled trial. *Lancet*. 2016;388:1170-1182. doi:10.1016/S0140-6736(16)31325-3	
Monteiro-Junior RS, Figueiredo LFDS, Maciel-Pinheiro PDT, et al. Virtual reality–based physical exercise with exergames (PhysEx) improves mental and physical health of institutionalized older adults. *J Am Med Dir Assoc*. 2017;18:454.e1-454.e9. doi:10.1016/j.jamda.2017.01.001	
Montero-Alía P, Miralles-Basseda R, López-Jiménez T, et al. Controlled trial of balance training using a video game console in community-dwelling older adults. *Age Ageing*. 2019;48:506-512. doi:10.1093/ageing/afz047	
Morat M, Bakker J, Hammes V, et al. Effects of stepping exergames under stable versus unstable conditions on balance and strength in healthy community-dwelling older adults: A three-armed randomized controlled trial. *Exp Gerontol*. 2019;127:110719. doi:10.1016/j.exger.2019.110719	
Padala KP, Padala PR, Malloy TR, et al. Wii-fit for improving gait and balance in an assisted living facility: A pilot study. *J Aging Res*. 2012;2012. doi:10.1155/2012/597573	
Park EC, Kim SG, Lee CW. The effects of virtual reality game exercise on balance and gait of the elderly. *J Phys Ther Sci*. 2015;27:1157-1159. doi:10.1589/jpts.27.1157	
Pichierri G, Murer K, de Bruin ED. A cognitive-motor intervention using a dance video game to enhance foot placement accuracy and gait under dual task conditions in older adults: A randomized controlled trial. *BMC Geriatr*. 2012;12:74. doi:10.1186/1471-2318-12-74	
Pitta A, Pereira G, Lara JPR, et al. The Effects of Different Exergame Intensity Training on Walking Speed in Older Women. *Games Health J*. 2020;9:121-128. doi:10.1089/g4h.2019.0109	Post Intervention: Groups incomparable (Note. Reports outcomes from same study as Santos et al. 2019.)
Pluchino A, Lee SY, Asfour S, Roos BA, Signorile JF. Pilot study comparing changes in postural control after training using a video game balance board program and 2 standard activity-based balance intervention programs. *Arch Phys Med Rehabil*. 2012;93:1138-1146. doi:10.1016/j.apmr.2012.01.023	
Ray C, Melton F, Ramirez R, Keller D. The effects of a 15-week exercise intervention on fitness and postural control in older adults. *Act Adapt Aging*. 2012;36:227-241. doi:10.1080/01924788.2012.696236	
Rendon AA, Lohman EB, Thorpe D, Johnson EG, Medina E, Bradley B. The effect of virtual reality gaming on dynamic balance in older adults. *Age*	

Ageing. 2012;41:549-552. doi:10.1093/ageing/afs053	
Rutkowski S, Rutkowska A, Jastrzebski D, Racheniuk H, Pawelczyk W, Szczegielniak J. Effect of virtual reality-based rehabilitation on physical fitness in patients with chronic obstructive pulmonary disease. *J Hum Kinet*. 2019;69:149-157. doi:10.2478/hukin-2019-0022	
Sajid S, Dale W, Mustian K, et al. Novel physical activity interventions for older patients with prostate cancer on hormone therapy: A pilot randomized study. *J Geriatr Oncol*. 2016;7:71-80. doi:10.1016/j.jgo.2016.02.002	Post Intervention & Post follow-up: Numerical data not available
Santamaría KG, Fonseca AS, Jiménez JM, Mora LCS. Balance, attention and concentration improvements following an exergame training program in elderly. *Retos-Nuevas Tendencias En Educ Fis Deport Y Recreacion*. 2018;2041:102-105.	
Santos GOR, Wolf R, Silva MM, Rodacki ALF, Pereira G. Does exercise intensity increment in exergame promote changes in strength, functional capacity and perceptual parameters in pre-frail older women? A randomized controlled trial. *Exp Gerontol*. 2019;116:25-30. doi:10.1016/j.exger.2018.12.009	Post Intervention: Groups incomparable (Note. Reports outcomes from same study as Pitta et al. 2019)
Sato K, Kuroki K, Saiki S, Nagatomi R. Improving walking, muscle strength, and balance in the elderly with an exergame using kinect: A randomized controlled trial. *Games Health J*. 2015;4:161-167. doi:10.1089/g4h.2014.0057	
Schoene D, Lord SR, Delbaere K, Severino C, Davies TA, Smith ST. A randomized controlled pilot study of home-based step training in older people using videogame technology. *PLoS One*. 2013;8:e57734-e57734. doi:10.1371/journal.pone.0057734	
Schwenk M, Grewal GS, Honarvar B, et al. Interactive balance training integrating sensor-based visual feedback of movement performance: A pilot study in older adults. *J Neuroeng Rehabil*. 2014;11:164. doi:10.1186/1743-0003-11-164	
Schättin A, Arner R, Gennaro F, de Bruin ED. Adaptations of prefrontal brain activity, executive functions, and gait in healthy elderly following exergame and balance training: A randomized-controlled study. *Front Aging Neurosci*. 2016;8. doi:10.3389/fnagi.2016.00278	
Segura-Ortí E, Pérez-Domínguez B, Ortega-Pérez de Villar L, et al. Virtual reality exercise intradialysis to improve physical function: A feasibility randomized trial. *Scand J Med Sci Sport*. 2019;29:89-94. doi:10.1111/sms.13304	
Singh DKA, Rajaratnam BS, Palaniswamy V, Raman VP, Bong PS, Pearson H. Effects of balance-focused interactive games compared to therapeutic balance classes for older women. *Climacteric*. 2013;16:141-146. doi:10.3109/13697137.2012.664832	
Smaerup M, Grönvall E, Larsen SB, Laessoe U, Henriksen J-J, Damsgaard EM. Computer-assisted training as a complement in rehabilitation of patients with chronic vestibular dizziness: A randomized controlled trial. *Arch Phys Med Rehabil*. 2015;96:395-401. doi:10.1016/j.apmr.2014.10.005	
Smaerup M, Laessoe U, Grönvall E, Henriksen JJ, Damsgaard EM. The use of computer-assisted home exercises to preserve physical function after a vestibular rehabilitation program: A randomized controlled study. *Rehabil Res Pract*. 2016;2016. doi:10.1155/2016/7026317	Post Intervention: Same participants as in Smaerup et al. 2015 study
Stanmore EK, Mavroeidi A, de Jong LD, et al. The effectiveness and cost-effectiveness of strength and balance Exergames to reduce falls risk for people aged 55 years and older in UK assisted living facilities: A multi-centre, cluster randomised controlled trial. *BMC Med*. 2019;17:49. doi:10.1186/s12916-019-1278-9	
Sutanto YS, Makhabah DN, Aphridasari J, Doewes M, Suradi AN. Videogame assisted exercise training in patients with chronic obstructive pulmonary disease: A preliminary study. *Pulmonology*. 2019;25:275-282. doi:10.1016/j.pulmoe.2019.03.007	
Szturm T, Betker AL, Moussavi Z, Desai A, Goodman V. Effects of an interactive	

computer game exercise regimen on balance impairment in frail community-dwelling older adults: A randomized controlled trial. *Phys Ther*. 2011;91:1449-1462. doi:10.2522/ptj.20090205	
Tollar J, Nagy F, Moizs M, Toth BE, Sanders LMJ, Hortobagyi T. Diverse exercises similarly reduce older adults' mobility limitations. *Med Sci Sports Exerc*. 2019;51:1809-1816. doi:10.1249/MSS.0000000000002001	
Toulotte C, Toursel C, Olivier N. Wii Fit (R) training vs. adapted physical activities: Which one is the most appropriate to improve the balance of independent senior subjects? A randomized controlled study. *Clin Rehabil*. 2012;26:827-835. doi:10.1177/0269215511434996	
Tsang WWN, Fu ASN. Virtual reality exercise to improve balance control in older adults at risk of falling. *Hong Kong Med J*. 2016;22:S19-S22.	
Uzor S, Baillie L. Recov-R: Evaluation of a home-based tailored exergame system to reduce fall risk in seniors. *Acm Trans Comput Interact*. 2019;26. doi:10.1145/3325280	
Villumsen BR, Jorgensen MG, Frystyk J, Hørdam B, Borre M. Home-based 'exergaming' was safe and significantly improved 6-min walking distance in patients with prostate cancer: A single-blinded randomised controlled trial. *BJU Int*. 2019;124:600-608. doi:10.1111/bju.14782	Post Follow-up: walking outcomes were not measured
Yeşilyaprak SS, Yildirim MŞ, Tomruk M, Ertekin Ö, Algun ZC. Comparison of the effects of virtual reality-based balance exercises and conventional exercises on balance and fall risk in older adults living in nursing homes in Turkey. *Physiother Theory Pract*. 2016;32:191-201. doi:10.3109/09593985.2015.1138009	
Yuen HK, Lowman JD, Oster RA, de Andrade JA. Home-based pulmonary rehabilitation for patients with idiopathic pulmonary fibrosis: A pilot study. *J Cardiopulm Rehabil Prev*. 2019;39:281-284. doi:10.1097/HCR.0000000000000418	

Table B2. Excluded studies (n=152) with justification for exclusion.

Studies excluded from the review	Reason for exclusion
Alahmari KA, Sparto PJ, Marchetti GF, Redfern MS, Furman JM, Whitney SL. Comparison of virtual reality based therapy with customized vestibular physical therapy for the treatment of vestibular disorders. *Ieee Trans Neural Syst Rehabil Eng*. 2014;22:389-399.	Wrong intervention
Anderson-Hanley C, Arciero PJ, Westen SC, Nimon J, Zimmerman E. Neuropsychological benefits of stationary bike exercise and a cybercycle exergame for older adults with diabetes: An exploratory analysis. *J Diabetes Sci Technol*. 2012;6:849-857.	Wrong outcomes
Anson E, Ma L, Meetam T, et al. Trunk motion visual feedback during walking improves dynamic balance in older adults: Assessor blinded randomized controlled trial. *Gait Posture*. 2018;62:342-348.	Wrong intervention
Bade MJ. Improving strength and function after total knee arthroplasty. *Diss Abstr Int Sect B Sci Eng*. 2013;74.	Conference proceeding
Barcelos N, Shah N, Cohen K, et al. Aerobic and cognitive exercise (ACE) pilot study for older adults: Executive function improves with cognitive challenge while exergaming. *J Int Neuropsychol Soc*. 2015;21:768-779.	Wrong outcomes
Bondoc S, Hewitt P, Frey N, McQuide B, Johnson A. The effect of wii-based interventions on physical, cognitive and social functioning among pre-frail elderly persons. *Arch Phys Med Rehabil*. 2011;92:1700.	Conference proceeding
Brumels KA, Blasius T, Cortright T, Oumedian D, Solberg B. Comparison of efficacy between traditional and video game based balance programs. *Clin Kinesiol J Am Kinesiotherapy Assoc*. 2008;62:26-31.	Wrong participant group
Cacau L de AP, Oliveira GU, Maynard LG, et al. The use of the virtual reality as intervention tool in the postoperative of cardiac surgery. *Rev Bras Cir Cardiovasc*. 2013;28:281-289.	Wrong participant group
Carvalho IF de, Leme GLM, Scheicher ME. The influence of video game training with and without subpatelar bandage in mobility and gait speed on elderly female fallers. *J Aging Res*. Published online 2018:1-6.	Wrong comparator
Cawthorne D, March L, Parker D, Coolican M, Negus J. TKR-power-patient outcomes using wii enhanced rehabilitation after a total knee replacement. *Physiother (United Kingdom)*. 2015;101:eS204-eS205.	Conference proceeding
Chen C-C. Improvement in the physiological function and standing stability based on kinect multimedia for older people. *J Phys Ther Sci*. 2016;28:1343-1348.	Wrong study design
Chen P-Y, Wei S-H, Hsieh W-L, Cheen J-R, Chen L-K, Kao C-L. Lower limb power rehabilitation (LLPR) using interactive video game for improvement of balance function in older people. *Arch Gerontol Geriatr*. 2012;55:677-682.	Wrong study design
Cho GH, Hwangbo G, Shin HS. The effects of virtual reality-based balance training on balance of the elderly. J Phys Ther Sci. 2014;26:615-617.	Wrong outcomes
Chuang T-Y, Sung W-H, Lin C-Y. Application of a virtual reality-enhanced exercise protocol in patients after coronary bypass. *Arch Phys Med Rehabil*. 2005;86:1929-1932.	Wrong intervention
Collado-Mateo D, Dominguez-Munoz FJ, Adsuar JC, Merellano-Navarro E, Gusi N. Exergames for women with fibromyalgia: A randomised controlled trial to evaluate the effect on mobility skills, balance and fear of falling. *PeerJ*. 2017;5.	Wrong participant group
Correia FD, Nogueira A, Magalhaes I, et al. Home-based rehabilitation with a novel digital biofeedback system versus conventional in-person rehabilitation after total knee replacement: A feasibility study. *Sci Rep*. 2018;8.	Wrong study design
Cutter CJ, Schottenfeld RS, Moore BA, et al. A pilot trial of a videogame-based exercise program for methadone maintained patients. *J Subst Abuse Treat*. 2014;47:299-305.	Wrong participant group
da Silva Vieira AS, de Melo MCDA, Pinho ARSN., Machado JP, Mendes JGM. The effect of virtual reality on a home-based cardiac rehabilitation program on body composition, lipid profile and eating patterns: A	Wrong intervention

randomized controlled trial. *Eur J Integr Med*. 2017;9:69-78.	
Dahl-Popolizio S, Loman J, Cordes CC. Comparing outcomes of kinect videogame-based occupational/physical therapy versus usual care. *Games Health J*. 2014;3:157-161.	Wrong participant group
Daniel KM, Ray C, Cason C. Progressive functional wii-hab in pre-frail older adults. *J Am Geriatr Soc*. 2011;59:S157-S157.	Conference proceeding
Duque G, Boersma D, Loza-Diaz G, et al. Effects of balance training using a virtual-reality system in older fallers. *Clin Interv Aging*. 2013;8:257-263.	Wrong outcomes
Elshazly FAA, Nambi SG, Elnegamy TE. Comparative study on virtual reality training (VRT) over sensory motor training (SMT) in unilateral chronic osteoarthritis: A randomized control trial. *Int J Med Res Heal Sci*. 2016;5:7-16.	Wrong participant group
Fitzgerald D, Rakarnratanakul N, Smyth B, Caulfield B. Effects of a wobble board-based therapeutic exergaming system for balance training on dynamic postural stability and intrinsic motivation levels. *J Orthop Sports Phys Ther*. 2010;40:11-19.	Wrong participant group
França dos Santos F, Nunes Magalhães LHV, Nunes de Sousa FA, de Oliveira Marques C, Torres MV, Santos Leal S. Analysis of virtual reality versus functional training in fitness for elderly women. *ConScientiae Saude*. 2015;14:117-124.	Other than Finnish, English, German or Spanish
Franco JR, Jacobs K, Inzerillo C, Kluzik J. The effect of the Nintendo Wii Fit and exercise in improving balance and quality of life in community dwelling elders. *Technol Health Care*. 2012;20:95-115.	Wrong outcomes
Fu A., Gao KL, Tung AK, Tsang WW, Kwan MM. The effectiveness of exergaming training for reducing fall risk and incidence among the frail older adults with a history of falls. *Arch Phys Med Rehabil*. 2015;96:2096-2102.	Wrong outcomes
Fung V, Ho A, Shaffer J, Gomez M. The utilization of nintendo wii fit in the rehabilitation of outpatients following total knee replacements: Preliminary results of a randomized controlled trial. *Arch Phys Med Rehabil*. 2010;91:e37-e37.	Conference proceeding
Fung V, Shaffer J, Chung E, Ho A, Gomez M. The utilization of nintendo Wii FitTM in the rehabilitation of outpatients following total knee replacements: A randomized controlled trial. *Physiother (United Kingdom)*. 2011;97:eS419-eS419	Conference proceeding
Fung V, Ho A, Shaffer J, Chung E, Gomez M. Use of Nintendo Wii FitTM in the rehabilitation of outpatients following total knee replacement: A preliminary randomised controlled trial. *Physiotherapy*. 2012;98:183-188. doi:10.1016/j.physio.2012.04.001	Duplicate
Garcia AP, Gananca MM, Cusin FS, Tomaz A, Gananca FF, Caovilla HH. Vestibular rehabilitation with virtual reality in Meniere's disease. *Braz J Otorhinolaryngol*. 2013;79:366-374.	Wrong participant group
Garcia-Hernandez N, Garza-Martinez K, Parra-Vega V, Alvarez-Sanchez A, Conchas-Arteaga L. Development of an EMG-based exergaming system for isometric muscle training and its effectiveness to enhance motivation, performance and muscle strength. *Int J Hum Comput Stud*. 2019;124:44-55.	Wrong participant group
Garcia-Palacios A, Herrero R, Vizcaino Y, et al. Integrating virtual reality with activity management for the treatment of fibromyalgia: Acceptability and preliminary efficacy. *Clin J Pain*. 2015;31:564-572.	Wrong intervention
Guimaraes, A. Heart rate variability in older adults undergoing exergames and aerobic exercise training: A randomised controlled trial. *J Phys Act Health*. 2018;15:S212-S212.	Conference proceeding
Hendriks MMC, Buise MP. Interactive video games for rehabilitation in the intensive care unit: A pilot study. *J Crit Care*. 2019;51:24-25.	Wrong study design
Ho SF, Thomson A, Kerr A. Feedback integrated rehabilitation for sit-to-stand training (first): A pilot randomised controlled trial. *Age Ageing*. 2018;47:iii20-iii20	Conference proceeding
Hsia SH, Magliano LA, Sanchez H, Storer TW. "Dance dance revolution"	Conference proceeding

exergaming vs. treadmill exercise in type 2 diabetes. *Diabetes*. 2013;62:A186-A187.	
Hsieh C-C, Lin P-S, Hsu W-C, et al. The effectiveness of a virtual reality-based Tai Chi exercise on cognitive and physical function in older adults with cognitive impairment. *Dement Geriatr Cogn Disord*. 2019;46:358-370.	Duplicate
Hsieh C-C, Lin P-S, Hsu W-C, et al. The effectiveness of a virtual reality-based Tai Chi exercise on cognitive and physical function in older adults with cognitive impairment. *Dement Geriatr Cogn Disord*. Published online 2018:358-370.	Wrong study design
Hsu JK, Thibodeau R, Wong SJ, Zukiwsky D, Cecile S, Walton DM. A “Wii” bit of fun: The effects of adding Nintendo Wii Bowling to a standard exercise regimen for residents of long-term care with upper extremity dysfunction. *Physiother Theory Pract*. 2011;27:185-193.	Wrong outcomes
Hsu S-Y, Fang T-Y, Yeh S-C, Su M-C, Wang P-C, Wang VY. Three-dimensional, virtual reality vestibular rehabilitation for chronic imbalance problem caused by Meniere’s disease: A pilot study. *Disabil Rehabil*. 2017;39:1601-1606.	Wrong outcomes
Ibrahim MS, Mattar AG, Elhafez SM. Efficacy of virtual reality-based balance training versus the Biodex balance system training on the body balance of adults. *J Phys Ther Sci*. 2016;28:20-26.	Wrong participant group
Jin, C.; Feng, Y. J.; Ni, Y. J.; Shan ZL. Virtual reality intervention in postoperative rehabilitation after total knee arthroplasty: A prospective and randomized controlled clinical trial. *Int J Clin Exp Med*. 2018;11:6119-6124.	Wrong intervention
Jo EA, Wu SS, Han HR, Park JJ, Park SJ, Cho KI. Effects of exergaming in postmenopausal women with high cardiovascular risk: A randomized controlled trial. *Clin Cardiol*. Published online 2019:1-8.	Wrong outcomes
Jo EA, Wu SS, Han HR, Cho KI. Impact of exergame vs. treadmill exercise on cardiorespiratory fitness, endothelial function and epicardial fat thickness in patients with high cardiovascular risk. *Eur Heart J*. 2018;39:20-20.	Conference proceeding
Karahan AY, Tok F, Yildirim P, Ordahan B, Turkoglu G, Sahin N. The effectiveness of exergames in patients with ankylosing spondylitis: A randomized controlled trial. *Adv Clin Exp Med*. 2016;25:931-936.	Wrong outcomes
Karakoc ZB, Colak TK, Sari Z, Polat MG. The effect of virtual rehabilitation added to an accelerated rehabilitation program after anterior cruciate ligament reconstruction: A randomized controlled trial. *Clin Exp Heal Sci*. 2019;9:124-129.	Wrong participant group
Karssemeijer EGA, Bossers WJR, Aaronson JA, Sanders LMJ, Kessels RPC, Rikkert M. Exergaming as a physical exercise strategy reduces frailty in people with dementia: A randomized controlled trial. *J Am Med Dir Assoc*. 2019;20:1502-1508.	Wrong intervention
Kempf K, Martin S. Autonomous use of the exercise game Wii Fit Plus improves glucometabolic control and quality of life in type 2 diabetes patients: A randomized controlled trial. *Diabetes*. 2013;62:A187-A187.	Conference proceeding
Kempf K, Martin S. Autonomous exercise game use improves metabolic control and quality of life in type 2 diabetes patients: A randomized controlled trial. *Bmc Endocr Disord*. 2013;13.	Wrong outcomes
Khalil AA, Mohamed GA, Abd El Rahman SM, Elhafez SM, Nassif, Nagui S. Effect of Wiihabilitation on strength ratio of ankle muscles in adults. *J Phys Ther Sci*. 2016;28:2862-2866.	Wrong participant group
Khushnood K, Sultan N, Mehmood R, Qureshi S, Tariq H, Amjad I. Does Wii Fit balance training improve balance and reduce fall risk in diabetic patients as compared to balance training exercises? *Rawal Med J*. 2019;44:44-48.	Wrong participant group
Kim J, Son J, Ko N, Yoon B. Unsupervised virtual reality-based exercise program improves hip muscle strength and balance control in older adults: A pilot study. *Arch Phys Med Rehabil*. 2013;94:937-943.	Wrong outcomes
Kim KJ, Heo M. Effects of virtual reality programs on balance in functional ankle instability. *J Phys Ther Sci*. 2015;27:3097-3101.	Wrong participant group

Kim KJ, Heo M. Comparison of virtual reality exercise versus conventional exercise on balance in patients with functional ankle instability: A randomized controlled trial. *J Back Musculoskelet Rehabil*. 2019;32:905-911.	Wrong participant group
Kim K, Choi B, Lim W. The efficacy of virtual reality assisted versus traditional rehabilitation intervention on individuals with functional ankle instability: A pilot randomized controlled trial. *Disabil Rehabil Assist Technol*. 2019;14:276-280.	Wrong participant group
Kim S-S, Min W-K, Kim J-H, Lee B-H. The effects of VR-based Wii Fit Yoga on physical function in middle-aged female LBP patients. *J Phys Ther Sci*. 2014;26:549-552.	Wrong intervention
Kimhy D, Vakhrusheva J, Bartels MN, et al. A single-blind randomized clinical trial of aerobic exercise in individuals with schizophrenia: Impact on brain-derived neurotrophic factor and neurocognition. *Schizophr Bull*. 2015;41:S83-S83.	Conference proceeding
Konstantinidis EI, Billis AS, Mouzakidis CA, Zilidou VI, Antoniou PE, Bamidis PD. Design, implementation, and wide pilot deployment of FitForAll: An easy to use exergaming platform improving physical fitness and life quality of senior citizens. *Ieee J Biomed Heal Informatics*. 2016;20:189-200	Wrong study design
Kotrach H, Dajczman E, Tremblay G, et al. A pilot study using virtual game system to maintain adherence to home-based exercise following pulmonary rehabilitation in chronic obstructive pulmonary disease. *Chest*. 2015;148.	Conference proceeding
Kwok BC, Pua YH. Effects of WiiActive exercises on fear of falling and functional outcomes in community-dwelling older adults: A randomised control trial. *Age Ageing*. 2016;45:621-627. doi:10.1093/ageing/afw108	Duplicate
Lee D, Sangyong L, Park J. Effects of indoor horseback riding and virtual reality exercises on the dynamic balance ability of normal healthy adults. *J Phys Ther Sci*. 2014;26:1903-1905.	Wrong study design
Lee J, Yoo H-N, Lee B-H. Effects of augmented reality-based Otago exercise on balance, gait, and physical factors in elderly women to prevent falls: A randomized controlled trial. *J Phys Ther Sci*. 2017;29:1586-1589.	Wrong intervention
Lee SW, Song CH. Virtual reality exercise improves balance of elderly persons with type 2 diabetes: A randomized controlled trial. *J Phys Ther Sci*. 2012;24:261-265.	Wrong outcomes
Leutwyler H, Hubbard E, Cooper BA, Dowling G. Impact of a pilot videogame-based physical activity program on walking speed in adults with schizophrenia. *Community Ment Health J*. 2018;54:735-739.	Wrong participant group
Liao Y-Y, Hsuan CI, Lin Y-J, Chen Y, Hsu W-C. Effects of virtual reality-based physical and cognitive training on executive function and dual-task gait performance in older adults with mild cognitive impairment: A randomized control trial. *Front Aging Neurosci*. 2019;10.	Duplicate
Makhabah D, Suradi S, Doewes M. The role of interactive game-based system in pulmonary rehabilitation of patients with COPD. *Eur Respir J*. 2015;46.	Conference proceeding
Martin-Martinez JP, Villafaina S, Collado-Mateo D, Perez-Gomez J, Gusi N. Effects of 24-week exergame intervention on physical function under single- and dual-task conditions in fibromyalgia: A randomized controlled trial. *Scand J Med Sci Sports*. 2019;29:1610-1617.	Wrong participant group
Mastel-Smith B, Duke G, He Z. A pilot randomized controlled trial examining the effects of Tai Chi and electronic tablet use on older adults' cognition and health. *J Holist Nurs*. 2019;37:163-174.	Wrong intervention
Maynard LG, de Menezes DL, Liao NS, et al. Effects of exercise training combined with virtual reality in functionality and health-related quality of life of patients on hemodialysis. *Games Health J*. 2019;8:339-348.	Wrong participant group
Mazzoleni S, Montagnani G, Vagheggini G, et al. Interactive videogame as rehabilitation tool of patients with chronic respiratory diseases: Preliminary results of a feasibility study. *Respir Med*. 2014;108:1516-1524.	Wrong outcomes

McBain T, Weston M, Crawshaw P, Haighton C, Spears I. Development of an exergame to deliver a sustained dose of high-intensity training: Formative pilot randomized trial. *Jmir Serious Games*. 2018;6:e4.	Wrong participant group
McCarthy H, Brazil ST, Greene JC, Rendell ST, Rohr LE. The impact of Wii Fit™ yoga training on flexibility and heart rate. *Int Sport J*. 2013;14:67-76.	Wrong intervention
Meldrum D, Herdman S, Vance R, et al. Effectiveness of conventional versus virtual reality-based balance exercises in vestibular rehabilitation for unilateral peripheral vestibular loss: Results of a randomized controlled trial. *Arch Phys Med Rehabil*. 2015;96:1319-1328.e1.	Wrong participant group
Micarelli A, Viziano A, Augimeri I, Micarelli D, Alessandrini M. Three-dimensional head-mounted gaming task procedure maximizes effects of vestibular rehabilitation in unilateral vestibular hypofunction: A randomized controlled pilot trial. *Int J Rehabil Res*. 2017;40:325-332.	Wrong participant group
Montagnani G, Makhabah D, Vagheggini G, et al. Effectiveness of add-on interactive video games exercises in pulmonary rehabilitation programs in chronic respiratory diseases patient. *Eur Respir J*. 2013;42.	Conference proceeding
Monteiro-Junior RS, de Souza CP, Lattari E, et al. Wii-Workouts on chronic pain, physical capabilities and mood of older women: A randomized controlled double blind trial. *CNS Neurol Disord Drug Targets*. 2015;14:1157-1164.	Wrong outcomes
Morone G, Paolucci T, Luziatelli S, et al. Wii Fit is effective in women with bone loss condition associated with balance disorders: A randomized controlled trial. *Aging Clin Exp Res*. 2016;28:1187-1193.	Wrong outcomes
Morrison S, Simmons R, Colberg SR, Parson HK, Vinik AI. Supervised balance training and Wii Fit–based exercises lower falls risk in older adults with type 2 diabetes. *J Am Med Dir Assoc*. 2018;19:185.e7-185.e13.	Wrong outcomes
Mugueta-Aguinaga I, Garcia-Zapirain B. FRED: Exergame to prevent dependence and functional deterioration associated with ageing. A pilot three-week randomized controlled clinical trial. *Int J Environ Res Public Health*. 2017;14.	Wrong outcomes
Mugueta-Aguinaga I, Garcia-Zapirain B. Frailty level monitoring and analysis after a pilot six-week randomized controlled clinical trial using the FRED exergame including biofeedback supervision in an elderly day care centre. *Int J Environ Res Public Health*. 2019;16.	Wrong outcomes
Najafi B, Grewal G, Lee-Eng J, Talal TK, Menzies RA, Armstrong DG. Game-based guided exercise: Using an avatar with real-time feed back to improve postural stability in diabetic peripheral neuro pathy. *Diabetes*. 2014;63:A186-A186.	Conference proceeding
NCT01741402. Effects of training in a virtual environment in healthy elderly. *Eff Train a Virtual Environ Perform Gait, Postural Control Exec Funct Heal Elder*. Published online 2012.	Ongoing study
NCT02333214. Effectiveness of a program using video games associated with conventional physiotherapy in physical functioning in frail elderly compared to conventional physiotherapy. *Eff an Exerc Progr Using Video Games Assoc With Conv Physiother Phys Funct Frail Elder Comp to Conv Physiother randomized Clin Trial*. Published online 2015.	Ongoing study
NCT02413996. Effects of virtual reality rehabilitation in patients with total knee arthroplasty. *Eff Virtual Real Rehabil Patients With Total Knee Arthroplast a Randomised Control Trial*. Published online 2015.	Ongoing study
Nicholson VP, McKean M, Lowe J, Fawcett C, Burkett B. Six weeks of unsupervised Nintendo Wii Fit gaming is effective at improving balance in independent older adults. *J Aging Phys Act*. 2015;23:153-158.	Wrong study design
Oesch P, Kool J, Fernandez-Luque L, et al. Exergames versus self-regulated exercises with instruction leaflets to improve adherence during geriatric rehabilitation: A randomized controlled trial. *BMC Geriatr*. 2017;17.	Wrong outcomes
Ordnung M, Hoff M, Kaminski E, Villringer A, Ragert P. No overt effects of a 6-week exergame training on sensorimotor and cognitive function in older adults. A preliminary investigation. *Front Hum Neurosci*. 2017;11.	Wrong outcomes

Padala KP, Padala PR, Lensing SY, et al. Efficacy of Wii-Fit on static and dynamic balance in community dwelling older veterans: A randomized controlled pilot trial. *J Aging Res*. Published online 2017:1-9.	Wrong outcomes
Padala KP, Padala PR, Lensing SY, et al. Home-based exercise program improves balance and fear of falling in community-dwelling older adults with mild Alzheimer's disease: A pilot study. *J Alzheimers Dis*. 2017;59:565-574.	Wrong outcomes
Paolucci T, Morone G, Luziatelli S, et al. The efficacy of Wii Fit training vs. adapted physical activity in elderly subjects on balance: Preliminary results. *Ann Phys Rehabil Med*. 2014;57:e166-e166.	Conference proceeding
Parijat P, Lockhart TE, Liu J. Effects of perturbation-based slip training using a virtual reality environment on slip-induced falls. *Ann Biomed Eng*. 2015;43:958-967.	Wrong intervention
Park JH. Does cognition-specific computer training have better clinical outcomes than non-specific computer training? A single-blind, randomized controlled trial. *Clin Rehabil*. 2018;32:213-222.	Wrong outcomes
Park J, Yim J. A new approach to improve cognition, muscle strength, and postural balance in community-dwelling elderly with a 3-D virtual reality Kayak program. *Tohoku J Exp Med*. 2016;238:1-8.	Wrong intervention
Park J-H, Lee S-H, Ko D-S. The effects of the Nintendo Wii exercise program on chronic work-related low back pain in industrial workers. *J Phys Ther Sci*. 2013;25:985-988.	Wrong participant group
Park Y-J, Yoo H, Im J-H, et al. Comparison of proprioception, lower limb stability, blood pressure and ROM after proprioceptive exercise by AR exercise and therapist instruction. *Medico-Legal Updat*. 2019;19:500-506.	Wrong intervention
Parker M, Delahunty B, Heberlein N, et al. Interactive gaming consoles reduced pain during acute minor burn rehabilitation: A randomized, pilot trial. *Burns*. 2016;42:91-96.	Wrong participant group
Paukowits S, Stoggl T. Balance trainability using the Nintendo Wii balance board in sportive people. *Sportverletz Sportschaden*. 2014;28:36-43.	Wrong participant group
Pavlou M, Kanegaonkar RG, Swapp D, Bamiou DE, Slater M, Luxon LM. The effect of virtual reality on visual vertigo symptoms in patients with peripheral vestibular dysfunction: A pilot study. *J Vestib Res*. 2012;22:273-281.	Wrong intervention
Phillips JS, Fitzgerald J, Phillis D, Underwood A, Nunney I, Bath A. Vestibular rehabilitation using video gaming in adults with dizziness: A pilot study. *J Laryngol Otol*. 2018;132:202-206.	Wrong outcomes
Pichierri G, Coppe A, Lorenzetti S, Murer K, de Bruin ED. The effect of a cognitive-motor intervention on voluntary step execution under single and dual task conditions in older adults: A randomized controlled pilot study. *Clin Interv Aging*. 2012;7:175-184.	Wrong outcomes
Piqueras M, Marco E, Coll M, et al. Effectiveness of an interactive virtual telerehabilitation system in patients after total knee arthoplasty: A randomized controlled trial. *J Rehabil Med*. 2013;45:392-396.	Wrong intervention
Piqueras M, Marco E, Coll M, et al. Effectiveness of an interactive virtual telerehabilitation system in patients after total knee arthroplasty: A randomized controlled trial. *J Rehabil Med*. 2013;45:392-396.	Duplicate
Pluchino AP, Lee SY, Asfour S, Roos BA, Signorile JF. Postural control changes following training using the Wii balance program and standardized falls prevention programs. *Med Sci Sport Exerc*. 2011;43:709-709.	Conference proceeding
Pooranawatthanakul K, Foongchomcheay A. Effect of video game commercial on short term balance training in Thai elderly. *Physiother (United Kingdom)*. 2015;101:eS398-eS398.	Conference proceeding
Prasertsakul T, Kaimuk P, Chinjenpradit W, Limroongreungrat W, Charoensuk W. The effect of virtual reality-based balance training on motor learning and postural control in healthy adults: A randomized preliminary study. *Biomed Eng Online*. 2018;17.	Wrong participant group

Punt IM, Ziltener J-L, Monnin D, Allet L. Wii FitTM exercise therapy for the rehabilitation of ankle sprains: Its effect compared with physical therapy or no functional exercises at all. *Scand J Med Sci Sports*. 2016;26:816-823.	Wrong participant group
Punt IM, Armand S, Ziltener J-L, Allet L. Effect of Wii FitTM exercise therapy on gait parameters in ankle sprain patients: A randomized controlled trial. *Gait Posture*. 2017;58:52-58.	Wrong participant group
Rendon AA. Virtual reality gaming as a tool for rehabilitation in physical therapy. Published online 2011.	Wrong study design
Rezaei I, Razeghi M, Ebrahimi S, Kayedi A, Rezaeian Z. A novel virtual reality technique (Cervigame) compared to conventional proprioceptive training to treat neck pain: A randomized controlled trial. *J Biomed Phys Eng*. 2019;9:355-366.	Wrong participant group
Rodrigues E V, Gallo LH, Guimarães ATB, Melo Filho J, Luna BC, Gomes ARS. Effects of dance exergaming on depressive symptoms, fear of falling, and musculoskeletal function in fallers and nonfallers community-dwelling older women. *Rejuvenation Res*. 2018;21:518-526.	Wrong study design
Rosiak O, Szczepanik M, Woszczak M, Lucas-Grzelczyk W, Jozefowicz-Korczynska M. Effectiveness of vestibular rehabilitation in patients with vestibular dysfunction. *Med Pr*. 2019;70:545-553.	Other than Finnish, English, German or Spanish
Ruivo JMADS, Karim K, O'Shea R, et al. In-class active video game supplementation and adherence to cardiac rehabilitation. *J Cardiopulm Rehabil Prev*. 2017;37:274-278.	Wrong outcomes
Sadeghi H, Hakim MN, Hamid TA, et al. The effect of exergaming on knee proprioception in older men: a randomized controlled trial [with consumer summary]. *Arch Gerontol Geriatr 2017 Mar-Apr;69144-150*. Published online 2017.	Wrong outcomes
Sadeghi H, Hakim MN, Hamid TA, et al. The effect of exergaming on knee proprioception in older men: A randomized controlled trial. *Arch Gerontol Geriatr*. 2017;69:144-150.	Duplicate
Sajid SS, Mustian K, Dale W, et al. A novel physical activity intervention using Wii-Fit improves physical performance in older prostate cancer patients on androgen deprivation therapy: An RCT. *J Am Geriatr Soc*. 2012;60:S73-S74.	Conference proceeding
Sapi M, Domjan A, Feherne Kiss A, Pinter S. Is Kinect training superior to conventional balance training for healthy older adults to improve postural control? *Games Health J*. 2019;8:41-48.	Wrong study design
Sarig Bahat H, Croft K, Carter C, Hoddinott A, Sprecher E, Treleaven J. Remote kinematic training for patients with chronic neck pain: A randomised controlled trial. *Eur Spine J*. 2018;27:1309-1323.	Wrong participant group
Sarig Bahat H, Takasaki H, Chen X, Bet-Or Y, Treleaven J. Cervical kinematic training with and without interactive VR training for chronic neck pain: A randomized clinical trial. *Man Ther*. 2015;20:68-78.	Wrong participant group
Scanlon A-M, Meldrum D, Belton A, Magnier A, Coleman K, O'Neill D. Use of Nintendo Wii® and its effect on the balance of older adults at risk of falls: A pilot RCT. *Physiother (United Kingdom)*. 2011;97:eS1105-eS1106.	Conference proceeding
Scanlon AM, Belton A, Magnier A, Coleman K, O'Neill D, Meldrum D. Use of Nintendo Wii® and its effect on the balance of older adults at risk of falls: A pilot randomised controlled trial. *Eur Geriatr Med*. 2010;1:S156-S156.	Conference proceeding
Schega L, Hamacher D, Wagenaar RC. A comparison of effects of augmented reality and verbal information based interventions in elderly women after hip replacement. *Arch Phys Med Rehabil*. 2011;92:1734-1735.	Conference proceeding
Schumacher H, Strüwe S, Greger N, et al. Prospective, randomized trial of physical function in patients before and after haematopoietic stem cell transplantation. *Bone Marrow Transplant*. 2015;50:S219-S219.	Conference proceeding
Schumacher H, Stuwe S, Kropp P, et al. A prospective, randomized evaluation of the feasibility of exergaming on patients undergoing hematopoietic stem cell transplantation. *Bone Marrow Transplant*. 2018;53:584-590.	Wrong participant group

Schwenk M, Grewal GS, Holloway D, Muchna A, Garland L, Najafi B. Interactive sensor-based balance training in older cancer patients with chemotherapy-induced peripheral neuropathy: A randomized controlled trial. *Gerontology*. 2016;62:553-563.	Wrong participant group
Shake MC, Crandall KJ, Mathews RP, Falls DG, Dispennette AK. Efficacy of Bingocize: A game-centered mobile application to improve physical and cognitive performance in older adults. *Games Health J*. 2018;7:253-261.	Wrong intervention
Sherrington C, Hassett L, van den Berg M, et al. The effectiveness of affordable technology in rehabilitation to improve mobility and physical activity: Amount (activity and mobility using technology) rehabilitation trial. *Ann Phys Rehabil Med*. 2018;61S:e86.	Conference proceeding
Signorile JF, Pluchino A, Lee SY, Asfour SS, Roos BA. Wii fit balance produces similar improvements in balance and postural control to formalized training. *J Am Geriatr Soc*. 2011;59:S18-S18.	Conference proceeding
Sims J, Cosby N, Saliba EN, Hertel J, Saliba SA. Exergaming and static postural control in individuals with a history of lower limb injury [with consumer summary]. *J Athl Train 2013 May-Jun;48:314-325*. Published online 2013.	Wrong participant group
Singh DKA, Rajaratnam BS, Palaniswamy V, Pearson H, Raman VP, Bong PS. Participating in a virtual reality balance exercise program can reduce risk and fear of falls. *Maturitas*. 2012;73:239-243	Wrong outcomes
Soares Andrade EC, dos Melo W, de Deus Dini P, Azevedo Pinheiro H. Using Nintendo ® Wii to balance training in institutionalized older people: Pilot study. *Fisioter Bras*. 2013;14:264-267.	Other than Finnish, English, German or Spanish
Sparrer I, Thien ADD, Ilgner J, Westhofen M. Vestibular rehabilitation using the Nintendo (R) Wii Balance Board - a user-friendly alternative for central nervous compensation. *Acta Otolaryngol*. 2013;133:239-245.	Wrong participant group
Srikesavan CS, Shay B, Szturm T. Task-oriented training with computer games for people with rheumatoid arthritis or hand osteoarthritis: A feasibility randomized controlled trial. *Games Health J*. 2016;5:295-303.	Wrong participant group
Tallon G, Seilles A, Melia G, et al. Effects of the serious game Medimoov on the functional autonomy of institutionalized older adults. *Ann Phys Rehabil Med*. 2015;58:e121-e122.	Conference proceeding
Taylor L, Kerse N, Klenk J, Borotkanics R, Maddison R. Exergames to improve the mobility of long-term care residents: A cluster randomized controlled trial. *Games Health J*. 2018;7:37-42. doi:10.1089/g4h.2017.0084	Wrong intervention
Thomas JS, France CR, Applegate ME, Leitkam ST, Walkowski S. Feasibility and safety of a virtual reality dodgeball intervention for chronic low back pain: A randomized clinical trial. *J Pain*. 2016;17:1302-1317.	Wrong participant group
Tsang WWN, Fong SSM, Tung KK, Fu ASN. Is virtual reality exercise effective in reducing falls among older adults with a history of falls? *Physiother (United Kingdom)*. 2015;101:eS1539-eS1540.	Conference proceeding
Vermeylen W, Delbroek T, Spildooren J. Effects of cognitive-motor dual task training with the Bio Rescue force platform on cognition, balance and dual task performance in institutionalized older adults. *Eur Geriatr Med*. 2016;7:S156-S156.	Conference proceeding
Whyatt C, Merriman NA, Young WR, Newell FN, Craig C. A Wii bit of fun: A novel platform to deliver effective balance training to older adults. *Games Health J*. 2015;4:423-433.	Wrong outcomes
Wi SY, Kang JH, Jang JH. Clinical feasibility of exercise game for depression treatment in older women with osteoarthritis: A pilot study. *J Phys Ther Sci*. 2013;25:165-167.	Wrong outcomes
Wibelinger LM, Batista JS, Vidmar MF, Miotto C, Pasqualotti A, Schneider RH. Conventional physiotherapy vs. wiiterapia: The effects on muscle strength in elderly women with knee osteoarthritis. *ConScientiae Saude*. 2013;12:90-96.	Other than Finnish, English, German or Spanish

Wiloth S, Werner C, Lemke NC, Bauer J, Hauer K. Motor-cognitive effects of a computerized game-based training method in people with dementia: A randomized controlled trial. *Aging Ment Health*. 2018;22:1124-1135.	Wrong outcomes
Wittelsberger R, Krug S, Tittlbach S, Bos K. The influence of Nintendo-Wii(R) bowling upon residents of retirement homes. *Zeitschrift für Gerontol + Geriatr*. 2013;46:425.	Wrong outcomes
Wonjae C, Seungwon L. The effects of virtual kayak paddling exercise on postural balance, muscle performance, and cognitive function in older adults with mild cognitive impairment: A randomized controlled trial. *J Aging Phys Act*. 2019;27:861-870.	Wrong intervention
Wu Y-Z, Lin J-Y, Wu P-L, Kuo Y-F. Effects of a hybrid intervention combining exergaming and physical therapy among older adults in a long-term care facility. *Geriatr Gerontol Int*. Published online 2018.	Wrong study design
Wu Y-Z, Lin J-Y, Wu P-L, Kuo Y-F. Effects of a hybrid intervention combining exergaming and physical therapy among older adults in a long-term care facility. *Geriatr Gerontol Int*. 2019;19:147-152.	Duplicate
Yaqoob I, Khan SU. Effectiveness of balance training on quality of life in osteoporotic women. *Rawal Med J*. 2018;43:328-331.	Wrong outcomes
Yeşilyaprak SS, Şenduran M, Tomruk M, Altin Ö, Algun ZC. The effects of exercises performed with virtual reality system on balance and fall risk in the elderly. *Fiz Rehabil*. 2014;25:S73-S74.	Conference proceeding
Yilmaz Yelvar GD, Cirak Y, Dalkilinc M, Parlak Demir Y, Guner Z, Boydak A. Is physiotherapy integrated virtual walking effective on pain, function, and kinesiophobia in patients with non-specific low-back pain? Randomised controlled trial. *Eur Spine J*. 2016;26:538-545.	Wrong intervention
Yilmaz DS, Baki AE. Effect of game based exercise programs on pain, functional mobility and balance in patients with knee osteoarthritis: Randomized controlled study. *Ann Rheum Dis*. 2019;78:498-499.	Conference proceeding
Yoon JE, Lee SM, Lim HS, Kim TH, Jeon JK, Mun MH. The effects of cognitive activity combined with active extremity exercise on balance, walking activity, memory level and quality of life of an older adult sample with dementia. *J Phys Ther Sci*. 2013;25:1601-1604.	Wrong intervention
Zadro JR, Shirley D, Simic M, et al. Video-game–based exercises for older people with chronic low back pain: A randomized controlled trial (GAMEBACK). *Phys Ther*. 2019;99:14-27.	Wrong outcomes
Zhou H, Al-Ali F, Ibrahimi A, et al. Game-based non-weight bearing exercise to improve motor performance in diabetic patients undergoing hemodialysis. *Hemodial Int*. 2017;21:A53-A53.	Conference proceeding

SUPLEMENTARY MATERIAL C: RESULTS

In this supplementary material C are

- characteristics of the individual RCTs included in the review (Table C1)
- reported exergaming protocols and technologies used in the studies included in the review (Table C2).
- risk of bias in studies included in the review (Figure C1).
- summary of risk of bias across RCTs included in the meta-analysis (Figure C2).
- “summary of findings” table (Table C3).

Table C1. Characteristics of the individual RCTs included in the review.

	Participants				Interventions						
Study and Country of Origin	**Group**	**N**	**Age (years)**	**Female %**	**Setting(s)**	**Duration (weeks)**	**Experimental**	**Comparison(s)**	**Sessions (x/week) / Session time (min)**	**Follow-up: Duration (weeks) / Procedure**	**Outcomes measuring walking**
Bacha et al. 2018 [1] Brazil	Community-dwelling	EG: 23 CG: 23	EG: 71.0 (66.0; 74.5) CG: 66.5 (65.0; 71.75)	EG: 65 CG: 83	Hospital clinic	7	Exercising with Xbox Kinect Adventures games	Conventional physical therapy exercises in a group-training program of six participants	2 / 60	4 / NR***)	FGA
Bieryla & Dold 2013 [2] USA	Independently living	EG: 6 CG: 6	EG: 82.5 (1.6) CG: 80.5 (7.8)	NR	EG: Laboratory CG: Home	3	Exercising with Wii fit games	Normal daily activities	EG: 3 / 30	3 / Normal daily activities***)	TUG
Bieryla 2016 [3] USA	Independently living	EG: 6 CG: 7	EG: 82 (2.4) CG: 82.6 (6.9)	NR	EG: Laboratory CG: Home	3	Exercising with Kinect-designed specific games	Normal daily activities	EG: 3 / 30	3 / Normal daily activities***)	TUG
Chow & Mann 2015 [4] China	Community-dwelling	EG: 10 CG: 10	EG: 70.4 (5.4) CG: 68.0 (3.0)	EG: 70 CG: 60	Elderly day activity centre	2	Cyber-golfing training	Regular table games	7 / 30-45	NA	TUG
Christiansen et al. 2015 [5] USA	TKR patients	EG: 13 CG: 13	EG: 68.2 (8.6) CG: 66.6 (8.1)	EG: 46 CG: 54	Acute care, outpatient clinic, home	6	Acute care: postoperative physical therapy protocol Home: standard of care home exercise program and Wii games	Acute care and outpatient: postoperative physical therapy protocol Home: standard of care home exercise program	Acute care: 14 Home: 7 / EG: 30 CG: NR	20 / NR***)	WS
Daniel 2012 [6] USA	Pre-frail	EG: 8 CG1: 8 CG2: 7	EG: 80 (3.37) CG1: 78.13 (5.5) CG2: 72.6 (4.6)	EG: 63 CG1: 63 CG2: 57	EG, CG1: Laboratory	15	Exercising with Wii Fit games with added weight vest	CG1: Community-based seated group exercise classes CG2: Normal daily activities	EG, CG1: 3 / 45	NA	TUG, 6MWT
Delbroek et al. 2017 [7] Belgium	Institutionalized with MCI	EG: 10 CG: 10	EG: 86.9 (5.6) CG: 87.5 (6.6)	EG: 80 CG: 50	Residential care centre	6	Virtual reality cognitive-motor dual-task training**)	Standard of usual care	EG: 2 / 18-30	NA	TUG, TUG Dual-task
Eggenberger et al. 2015 [8] Switzerland	Independently living or community-dwelling	EG: 24 CG1: 22 CG2: 25	EG: 77.3 (6.3) CG1: 78.5 (5.1) CG2: 80.8 (4.7)	EG: 58 CG1: 73 CG2: 64	EG, CG1: Outpatient clinic + home CG:2	26	Video game dancing in groups	CG1: Treadmill walking with simultaneous verbal memory training in groups CG2: Treadmill walking in groups	2 / 60	24 / Falls calendar***)	WS (habitual, fast), WS dual-task (habitual, fast), Gait variables

					Outpatient clinic						(habitual fast), 6MWT
Fung et al. 2012 [9] **Canada**	TKR patients	EG: 27 CG: 23	EG: 67.9 (9.5) CG: 68.2 (12.8)	EG: 58 CG: 42	Outpatient department of a rehabilitation hospital	5	Wii Fit gaming after physiotherapy session	lower extremity strengthening and balance exercises after physiotherapy session	2 / 15	NA	2MWT
Gomes et al. 2018 [10] **Brazil**	Frail	EG: 15 CG: 15	EG: 83 (5.87) CG: 85 (6.19)	NR	EG: Outpatient clinic	7	Exercising with Wii Fit Plus games	General advice of physical activity (WHO booklet)	EG: 2 / 50	4 / NR***)	FGA
Gschwind et al. 2015 [11] **Germany, Spain and Australia**	Community-dwelling	EG: 78 CG: 75	EG: 74.7 (6.7) CG: 74.7 (6.0)	EG: 56 CG: 67	Home*)	16	Exercising with individually tailored iStoppFalls game**)	Normal daily activities	EG: 3 + 3 / 45-120	8 / Falls calendar	TUG, WS, WS dual task
Htut et al. 2018 [12] **Thailand**	Community-dwelling	EG: 21 CG1: 21 CG2: 21 CG3: 21	EG: 75.8 (4.89) CG1: 75.9 (5.65) CG2: 75.6 (5.33) CG3: 76.0 (5.22)	EG: 52 CG1: 38 CG2: 43 CG3: 43	Homes for the aged	8	Exercising with Xbox 360 games	CG1: Strength and balance exercising CG2: Board and card games CG3: Normal daily activities	EG, CG1, CG2: 3 / 30	NA	TUG, TUG Dual-task
Hughes et al. 2014 [13] **USA**	MCI	EG: 10 CG: 10	EG: 78.5 (7.1) CG: 76.2 (4.3)	EG: 80 CG: 60	Centrally located church	24	Exercising with Nintendo Wii games in groups	Healthy aging education in groups	1 / 90	28 / NR***)	WS
Imam et al. 2017 [14] **Canada**	Community living individuals using the prosthesis after amputation of the lower limb	EG: 14 CG: 14	EG: 61.5 (50-78) CG: 62.5 (50-78)	EG: 14 CG: 43	Outpatient clinic, home*)	4	Exercising with Nintendo Wii Fit games	Training with Wii Big Brain games	3 / 40	3 / NR***)	2MWT
Jorgensen et al. 2013 [15] **Denmark**	Community-dwelling	EG: 28 CG: 30	EG: 75.9 (5.7) CG: 73.7 (6.1)	EG: 68 CG: 70	EG: Outpatient clinic CG: Home	10	Exercising with Nintendo Wii games in pairs	Daily use of EVA shoe insole	EG: 2 /30-40	NA	TUG
Jung et al. 2015 [16] **Republic of Korea**	At the risk for falls	EG: 8 CG1: 8 CG2: 8	EG: 74.3 (2.1) CG1: 74.3 (3.5) CG2: 73.6 (2.4)	100	Senior citizen centre	8	Exercising with Nintendo Wii Sport games	CG1: Lumbar stabilization exercises CG2: Normal daily activities	EG, CG1: 2 / 30	NA	TUG, Crossing velocity (CV), Maximum vertical heel clearance (MVHC)

Karahan et al. 2015 [17] **Turkey**	Rehabilitation clinic patients	EG: 48 CG: 42	EG: 71.3 (6.1) CG: 71.5 (4.7)	EG: 44 CG: 43	EG: Outpatient clinic CG: Home	6	Exercising with Xbox 360 games	Balance, stretching and strengthening exercises	5 / 30	NA	TUG
Ku et al. 2019 [18] **Republic of Korea**	Community-dwelling, ambulatory	EG: 18 CG: 16	EG: 64.7 (7.27) CG: 65.0 (4.77)	50	EG: Laboratory CG: Home	4	Exercising with the Kinect-designed specific games**)	lower-extremity strengthening and endurance training	3 / 30	NA	TUG
Kwok & Pua 2016 [19] **Singapore**	Moderately frail	EG: 40 CG: 40	EG: 70.5 (6.7) CG: 69.8 (7.5)	EG: 90 CG: 80	Laboratory and home	12	Exercising with Nintendo Wii Active games, additional home exercises	Gym exercises in groups, additional home exercises	1 / 60	12 + 28 / Home exercises and falls calendar***)	TUG, WS, 6MWT
Lauzé et al. 2017 [20] **Canada**	Aassisted living, moves independently within the residence	EG: 21 CG: 11	EG: 80.1 (7.5) CG:83.2 (6.7)	EG: 71 CG: 91	Assisted living residence*)	12	Exercising with Jintronix gaming system**)	Normal daily activities	EG: 2 / 45	12 / NR***)	TUG, WS
Lauzé et al. 2018 [21] **Canada**	Community living following a minor injury	EG: 6 CG: 6	EG: 73.17 (2.93) CG: 76 (6.51)	EG: 83 CG: 100	Home*)	12	Exercising with Jintronix gaming system**)	Normal daily activities	EG: 2 / 50-55	12 / NR***)	TUG, WS
Laver et al. 2012 [22] **Australia**	Hospitalised	EG: 22 CG: 22	EG: 85.2 (4.7) CG: 84.6 (4.4)	EG: 86 CG: 73	Rehabilitation unit at hospital	2	Exercising with Wii Fit games	Conventional physiotherapy	5 / 25	NA	TUG
Lee & Shin 2013 [23] **Republic of Korea**	Diabetics	EG: 27 CG: 28	EG: 73.78 (4.77) CG: 74.29 (5.20)	EG: 74 CG: 68	Welfare centre	10	Exercising with PS2 games in pairs + Health education (2 times)	Health education (2 times)	EG: 2 /50	NA	TUG, WS, Gait cadence
Lee et al. 2015 [24] **Republic of Korea**	Women	EG: 26 CG: 28	EG: 68.77 (4.62) CG: 67.71 (4.31)	100	Laboratory	8	Exercising with Xbox 360 games	Balance, coordination and strength exercises in group	3 / 60	NA	TUG
Lee et al. 2017 [25] **Republic of Korea**	Community-dwelling	EG: 21 CG: 19	EG: 76.15 (4.55) CG: 75.71 (4.91)	EG: 57 CG: 58	Senior welfare centre	6	Exercising with Wii Fit games in pairs + fall prevention education (3 times)	Fall prevention education (3 times)	EG: 2 / 60	NA	TUG

Liao et al. [26] **2019 Taiwan**	MCI	EG: 18 CG: 16	EG: 75.5 (5.2) CG: 73.1 (6.8)	EG: 61 CG: 75	Laboratory	12	Exercising with Kinect-designed specific games in groups**)	Combined physical and cognitive training in groups	3 / 60	NA	WS, WS Dual-task, WS Motor-task, Gait variables (Single-, Dual-, Motor-task)
Liao, Chen & Wang [27] **2019 Taiwan**	Pre-frail, frail	EG: 27 CG: 25	EG: 79.6 (8.5) CG: 84.1 (5.5)	EG: 70 CG: 68	Laboratory	12	Exercising with Kinect-designed specific games in groups**)	Combined physical training in groups	3 / 60	NA	TUG, WS
Lim et al. 2017 [28] **Republic of Korea**	Independent community living	EG: 10 CG: 10	EG: 77.30 (5.62) CG: 80.8 (5.14)	EG: 60 CG: 70	Laboratory	5	Combined exercises with Wii Fit Plus games	Balance exercise with Wii Fit Plus games	2 / 60	NA	TUG
Lin et al. [29] **2007 Taiwan**	Patients with knee OA	EG: 29 CG1: 26 CG2: 26	EG: 61.6 (8.1) CG1: 61.0 (7.7) CG2: 62.8 (6.3)	EG: 69 CG1: 81 CG2: 81	EG, CG1: Laboratory	8	Gamified proprioception exercises**)	CG1: Closed kinect chain exercises CG2: Health education (OA)	EG,CG1: 3 / 50	NA	WS (Ground level, Stairs, Spongy Surface, Figure 8)
Maillot et al. 2012 [30] **France**	Sedentary lifestyle	EG: 15 CG: 15	EG: 73.47 (4.10) CG: 73.47 (3.00)	NR	EG: Laboratory	12	Exercising with Wii Fit games in pairs	Normal daily activities	EG: 2 / 60	NA	TUG, 6MWT
Maillot et al. 2014 [31] **France**	Sedentary lifestyle	EG: 8 CG: 8	EG: 74.13 (4.73) CG: 74.00 (2.14)	NR	EG: Outpatient	12	Exercising with Wii Fit games in pairs	Normal daily activities	EG: 2 / 60	NA	TUG, 6MWT
Martel et al. 2018 [32] **Canada**	Community living following a minor injury	EG: 16 CG1: 16 CG2: 12	EG: 74.9 (7.1) CG1: 72.9 (6.7) CG2: 72.7 (6.5)	EG: 75 CG1: 63 CG2: 75	EG: Home*) CG1: Community centre	12	Exercising with Jintronix gaming system**)	CG1: Combined physical training in groups CG2: Normal daily activities	EG, CG1: 2 / 55	NA	TUG, WS, SPPB walking
Micarelli et al. 2019 [33] **Italy**	UVH / UVH + MCI	EG: 12 / 12 CG: 11 / 12	EG: 74.3 (4.7) / 72.5 (3.6) CG: 76.9 (4.7) / 76.3 (5.5)	EG: 50 / 58 CG: 55 / 58	Home*) and policlinic	4	Vestibular rehabilitation and exercising with HMD games	Vestibular rehabilitation	4 / 30-45	NA	DGI
Mirelman et al. 2016 [34] **Belgium, Israel, Italy, the Netherlands, and the UK**	Fallers / MCI	Fallers: 109 MCI: 43	EG: 75.4 (6.2) / 80.3 (5.2) CG: 75.6 (6.2) / 74.5 (5.4)	NR	Clinical centre	6	Combined treadmill training with VR component**)	Treadmill training	3 / 45	26 / Falls calendar***)	WS during obstacle negotiation, 2MWT

Monteiro-Junior et al. 2017 [35] **Brazil**	Living at long term care institution	EG: 9 CG: 9	EG: 85 (8) CG: 86 (5)	67	Long term-care institution	8	Exercising with Wii Fit games	Physical exercise	2 / 30-45	NA	TUG, WS, Gait variables
Montero-Alía et al. 2019 [36] **Spain**	Primary care centre visitors	EG:508 CG: 469	EG: 75.1 (72.6–78.7) CG: 75.4 (72.7–78.6)	EG: 62 CG: 53	Nursing home	12	Exercising with Wii Fit games	Normal daily activities	EG: 2 / 30	36 / Falls calendar***)	Tinetti's gait
Morat et al. 2019 [37] **Germany**	Community-dwelling	EG1: 15 CG1: 15 CG2: 15	EG1: 67.5 (5.1) CG1: 69.7 (6.2) CG2: 71.1 (5.2)	EG1: 67 CG1: 60 CG2: 60	EG1, CG1: Laboratory	8	Group exercising with Dividat Senso games under unstable conditions**)	CG1: Group exercising with Dividat Senso games under stable conditions CG2: Normal daily activities	EG1, CG1: 3 / 10-12	NA	TUG, TUG Dual-task
Padala et al. 2012 [38] **USA**	Mild AD	EG: 11 CG: 11	EG: 79.3 (9.8) CG: 81.6 (5.2)	73	Assisted living facility	8	Exercising with Wii Fit games	Indoor walking in groups	5 / 30	NA	TUG
Park et al. 2015 [39] **Republic of Korea**	Community-dwelling	EG: 12 CG: 12	EG: 66.5 (8.1) CG: 65.2 (7.9)	EG: 25 CG: 17	NR	8	Exercising with Wii Fit games	Ball exercises	3 / 30	NA	TUG
Pichierri et al. 2012 [40] **Switzerland**	Residents of hostels for the aged	EG: 11 CG: 11	EG: 86.9 (5.1) CG: 85.6 (4.2)	EG: 73 CG: 91	Senior citizens hostels	12	Resistance and balance training in groups and additional exercising with dancing game	Resistance and balance training in groups	2 / EG: 50-55 CG: 40	NA	WS (habitual, fast, cognitive, cognitive-fast) , Gait variables (habitual, fast, cognitive, cognitive-fast)
Pitta et al. 2020 [41] **/ Santos et al. 2019** [42] **Brazil**	Community-dwelling, pre-frail	EG: 11 CG: 9	EG: 69.7 (5.6) CG: 69.1 (5.0)	100	Laboratory	12	Vigorous exercising with Xbox 360 games	Moderate exercising with Xbox 360 games	3 / 40	NA	TUG, WS, WS fast, Gait variables (habitual, fast)
Pluchino et al. 2012 [43] **USA**	Independent community living	EG: 12 CG1: 14 CG2: 14	EG: 70.72 (8.46) CG1: 69.28 (6.03) CG2: 76.00 (7.74)	EG: 67 CG1: 57 CG2: 64	Laboratory*)	8	Exercising with Wii Fit games	CG1: Tai Chi CG2: Standard balance exercises	2 / 60	NA	TUG, Tinetti's gait

Ray et al. 2012 [44] **USA**	Moves independent, no falls	EG: 29 CG1: 40 CG2: 18	75	67	Community-dwelling	15	Exercising with Wii Fit games	CG1: Traditional senior fitness exercising CG2: Normal daily activities	EG, CG1: 3 / 45	NA	TUG, 6MWT
Rendon et al. 2012 [45] **USA**	Community-dwelling, at the risk for falls	EG: 20 CG: 20	EG: 85.7 (4.3) CG: 83.3 (6.2)	NR	EG: Outpatient clinic	6	Exercising with Wii Fit games	Normal daily activities	EG: 3 / 35-45	NA	TUG
Rutkowski et al. 2019 [46] **Poland**	Patients with COPD	EG: 34 CG: 34	EG: 60.5 (4.3) CG: 62.1 (2.9)	EG: 50 CG: 47	Hospital	2	Standard pulmonary rehabilitation in groups and additional exercising with Xbox 360 games	Standard pulmonary rehabilitation in groups	5 / EG: 75 CG: 60	NA	TUG, 6MWT
Sajid et al. 2016 [47] **USA**	Prostate cancer patients with hormone therapy	EG: 8 CG1: 6 CG2: 5	EG: 77.5 (6.7) CG1: 75.7 (9.5) CG2: 71.8 (5)	0	Home*)	6	Exercising with Wii Fit games	CG1: Aerobic and resistance exercising CG2: Normal daily activities	EG, CG1: 5 / NR	6 / EG, CG1: Continued exercising***)	6MWT
Santamaria et al. 2018 [48] **Costa Rica**	Senior citizens	EG: 14 CG: 13	EG: 63.21 (6.05) CG: 63.08 (5.74)	EG: 79 CG: 77	EG: Laboratory	5	Video game dancing in groups	Normal daily activities	EG: 3 / NR	NA	TUG
Sato et al. 2015 [49] **Japan**	Locally residing	EG: 28 CG: 26	EG: 70.07 (5.35) CG: 68.5 (5.47)	EG: 79 CG: 81	EG: Laboratory	7	Exercising with Kinect-designed specific games**)	Normal daily activities	EG: 2-3 / 40-60	NA	WS, Gait variables
Schoene et al. 2013 [50] **Australia**	Residents of independent-living units of a retirement village	EG: 15 CG: 17	EG: 77.5 (4.5) CG: 78.4 (4.5)	NR	EG: Home*)	8	Exercising with stepping game	Normal daily activities	EG: 2-3 / 15-20 (minim.)	NA	TUG, TUG dual-task
Schwenk et al. 2014 [51] **USA**	Residents in senior living community	EG: 17 CG: 16	EG: 84.3 (7.3) CG: 84.9 (6.6)	EG: 59 CG: 69	EG: Room in senior living community	4	Exercising with specific balance games**)	Normal daily activities	EG: 2 / 45	NA	TUG, WS (habitual, fast), Gait variability (habitual, fast)
Schättin et al. 2016 [52] **Switzerland**	Independently living or senior residency dwelling	EG: 13 CG: 14	EG: 80 (73 ; 83) CG: 80 (72.25 ; 81.75)	EG: 38 CG: 50	Senior residence dwelling	8	Exercising with specific Dividat games in groups**)	Conventional balance training in groups	3 / 30	NA	WS, Cadence and Stride length in four conditions (habitual, fast, dual- task, dual-task fast)

Segura-Orti et al. 2019 [53] **Spain**	HD patients	EG: 9 CG: 9	EG: 68.3 (15.6) CG: 61.8 (13.0)	EG: 33 CG: 44	Hospital	4	Exercising with Kinect-designed specific games	Aerobic and strengthening exercise	3 / 40	NA	WS, 6MWT
Singh et al. 2013 [54] **Malaysia**	Community-dwelling	EG: 18 CG: 18	EG: 61.12 (3.72) CG: 64.00 (5.88)	NR	Senior citizens´ club	6	Exercising with Wii Fit games	Balance exercises in group	2 / 40	NA	TUG
Smaerup et al. 2015 [55] **Denmark**	Patients with vestibular dysfunction	EG:30 CG: 30	EG: 76.65 (7.56) CG: 78.68 (6.56)	EG: 58 CG: 65	Hospital and home*)	16	Hospital: Rehabilitation training Home: Exercising with specific Mitii games**)	Hospital: Rehabilitation training Home: Exercising following printed instructions	Hospital: 2 Home: 7 / 20-30	NA	DGI
Smaerup et al. 2016 [56] **Denmark**	Patients with vestibular dysfunction	EG: 28 CG: 29	EG: 76.39 (7.63) CG: 78.93 (6.58)	EG: 57 CG: 63	Home*)	12	Exercising with specific Mitii games**)	Exercising following printed instructions	7 / 20-30	NA	DGI
Stanmore et al. 2019 [57] **UK**	Dwelling in assisted living facilities	EG: 56 CG: 50	EG: 77.9 (8.9) CG: 77.8 (10.2)	EG: 80 CG: 76	Sheltered housing	12	Exercising with Kinect-designed specific games**) and falls prevention exercising following program leaflet	Falls prevention exercising following program leaflet	EG: 3 / 15 (exergaming)	NA	TUG
Sutanto et al. 2019 [58] **Indonesia**	COPD patients	EG: 10 CG: 10	EG: 65.1 (7.5) CG: 65.6 (4.7)	EG: 10 CG: 0	Outpatient clinic	6	Outpatient exercising program and exercising with Wii Fit program	Outpatient exercising program	3 / EG: 60 CG: 30	NA	6MWT
Szturm et al. 2011 [59] **Canada**	Community-dwelling individuals with balance and mobility difficulties	EG: 15 CG: 15	EG: 80.5 (6) CG: 81 (7)	EG: 67 CG: 60	Geriatric day hospital	8	Exercising with specific video games**)	Strengthening and balance exercises	2 / 45	NA	TUG, WS, Gait variables
Tollar et al. 2019 [60] **Hungary**	Mobility-limited	EG: 28 CG1: 27 CG2: 28	EG: 69.2 (2.80) CG1: 70.2 (4.08) CG2: 69.5 (3.67)	EG: 50 CG1: 56 CG2: 54	EG: CG1: Hospital's PT gym	5	Exercising with Xbox 360 games	CG1: Cycling CG2: Normal daily activities	EG, CG1: 5 / 60	NA	6MWT, DGI
Toulotte et al. 2012 [61] **France**	Independently living	EG: 9 CG1: 9 CG2: 9 CG3: 9	EG: 72.2 (8.6) CG1: 76.4 (4.7) CG2: 84.2 (8.1) CG3: 71.8 (8.0)	EG: 56 CG1: 67 CG2: 67 CG3: 56	EG, CG1, CG2: Gymnasium	20	Exercising with Wii fit games	CG1: Exercising with Wii fit games + Adapted Physical activities training CG:2 Adapted physical activities training, CG3: Normal daily activities	EG, CG1, CG2: 1 / 60	NA	Tinetti's gait

Tsang & Fu 2016 [62] **China**	Nursing home residents with poor walking ability	EG: 39 CG: 40	EG: 82.3 (3.8) CG: 82.0 (4.3)	EG: 59 CG: 63	Nursing home	6	Exercising with the Wii balance games	Conventional balance training	3 / 60	NA	TUG
Uzor & Baillie 2019 [63] **England**	History of falls	EG: 16 CG: 22	EG: 76.4 (6.41) CG: 75.4 (6.04)	EG: 63 CG: 64	Home*)	8	Exercising with tailored exergame system**) in addition to standard care	Standard care (booklet, exercise video)	3 / 30 (minim.)	NA	WS
Villumsen et al. 2019 [64] **Denmark**	Patients with prostate cancer	EG: 23 CG: 23	EG: 67.6 (4.6) CG: 69.8 (4.4)	0	Home*)	12	Aerobic and strength exercises with Xbox360 games	Normal daily activities	EG: 3 / 60	12 / Physical activity diary	6MWT
Yeşilyaprak et al. 2016 [65] **Turkey**	History of falls	EG: 7 CG: 11	EG: 70.1 (4.0) CG: 73.1 (4.5)	EG: 43 CG: 82	Nursing home	6	Balance training with the VR rehabilitation system**)	Conventional balance training	3 / 45-55	NA	TUG
Yuen et al. 2019 [66] **USA**	Idiopathic Pulmonary Fibrosis patients	EG: 10 CG: 10	EG: 67.4 (7.4) CG: 72.2 (8.4)	EG: 50 CG: 20	Home*)	12	Exercising with Wii fit games	Cognitive video game training	3 / 30	NA	6MWT

EG = Experimental Group, CG = Comparison Group, NR = Not reported, NA = Not Applicable

Participants: Group; MCI = Mild Cognitive Impairment, TKR = Total Knee Replacement, OA = Osteoarthritis, UVH = Unilateral Vestibular Hypofunction, AD = Alzheimer's Disease, COPD = Chronic Obstructive Pulmonary Disease, HD = Hemodialysis, Age (years); Mean (SD), Medium/Median (Q1; Q3), Median (range), Female %; Rounded to even

Interventions: HMD = Head-Mounted Displays, Setting*) = unsuperviced exergaming, Experimental, **) = Game technology used developed for physical rehabilitation, Follow-up***) = Outcomes reassessed

Outcomes measuring walking: 2MWT = Two Minute Walking Test, 6MWT = Six Minute Walking Test, FGA = Functional Gait Assessment, TUG = Timed Up & Go, WS = Walking speed

Table C2. Reported exergaming protocols and used technologies in studies (n=66) included in the review.

			Exergaming protocol				Technology	
Study and Country of Origin	**Type of training**	**In addition to other exercising**	**Guidance**	**Super-viced**	**Session description**	**Progression**	**Hardware**	**Games made for rehabili-tation purposes**
Bacha et al. 2018 [1] Brazil	Exercising with Xbox Kinect Adventures games	N	Sessions guided by a physical therapist	Y	Participants trained with four games and were allowed five attempts at each game	Players engaged in games with the goal of obtaining the highest number of adventure points that affect game progression.	360 Xbox Kinect videogame console, Kinect sensor, TV	N
Bieryla & Dold 2013 [2] USA	Exercising with Wii fit games	N	Session were supervised, no physical assistance	Y	Participants trained yoga (half moon, chair, warrior), aerobic (torso twists), and balance games (soccer heading, ski jump). Exercising order was: yoga, aerobic, balance x2, yoga, aerobic	Participants were challenged consistently.	Nintendo Wii, Nintendo Wii Balance Board	N
Bieryla 2016 [3] USA	Exercising with the Kinect-designed specific games	N	Verbal instructions for the games were provided before starting the training. No physical assistance. When necessary, participants were reminded of the goal of the game during training.	Y	Participants trained with two Kinect games (Your Shape: Fitness Evolved and Kinect adventures)	NR	Kinect for Xbox 360	N
Chow & Mann 2015 [4] China	Cyber-golfing training	N	Golf swing demonstration sessions (2x30 min) given by trained research assistant before experimental procedures.	Y	Participants trained with "Tiger Woods PGA Tour 13 / The 10-hole gaming mode" games and were required to finish the whole game in every session	NR	Xbox 360 Kinect	N
Christiansen et al. 2015 [5] USA	Weight-bearing biofeedback exercise with Wii games	N	Physical therapist gave feedback on proper performance while participant was exergaming	Y	Participants trained with Wii Fit Plus games	Depending on participant's ability level, speed was increase and dynamic, unilateral and lunging activities were added	Nintendo Wii, Nintendo Wii Balance Board	N
Daniel 2012 [6] USA	Exercising with Wii fit games with added weight vest	N	Sessions were directed by staff	Y	Participants wore weight vest and trained with basic games such as bowling, tennis, and boxing	Core and quadriceps muscle groups were progressively overloaded with 2% of their body weight added to the weight vest every 2 weeks	Nintendo Wii	N

Delbroek et al. 2017 [7] Belgium	Virtual reality cognitive-motor dual-task training	N	Sessions were guided by a physical therapist, exergaming system gave real-time feedback on the movement of the centre of pressure	Y	While standing on platform, participants trained with nine games to train balance, weight bearing, memory, attention and dual tasking. Two 90-second break per session were allowed.	Difficulty levels were adjusted by participants' skill levels, duration of session was gradually increased from 18 to 30 minutes	BioRescue (RM Ingenierie, France; includes a platform (610 × 580 × 10 mm3)	Y
Eggenberger et al. 2015 [8] Switzerland	Video game dancing in groups	Y	Sessions were guided by two trained postgraduate students	Y	Participants did aerobic endurance training with video game dancing in addition to strength and balance exercises (20 minutes each)	To achieve moderate-to-vigorous exercise intensity, treadmill speed and inclination, step frequency in DANCE, or number of sets and repetitions were adapted	Impact Dance Platforms (Positive Gaming BV, Haarlem, the Netherlands), StepMania software	N
Fung et al. 2012 [9] Canada	Wii Fit gaming after physiotherapy session	Y	Sessions were guided by a physical therapist	Y	15 min Wii Fit games engaging in postural control and balance in addition to 60 min physiotherapy session	Protocol started with the 'Deep Breathing' and 'Ski Slalom' games and progressed to other games after top-level scoring	Nintendo Wii, Nintendo Wii Balance Board	N
Gomes et al. 2018 [10] Brazil	Exercising with Wii Fit Plus games	N	Sessions were guided by a physical therapist	Y	Participants played block A and B games (five 2-3 min games in each block) on alternate days. Each game was played twice in each session: first attempt with the manual guidance and verbal feedback, second attempt independently	NR	Nintendo Wii	N
Gschwind et al. 2015 [11] Germany, Spain and Australia	Exercising with individually tailored iStoppFalls game	N	Participants received safety guidance by an experienced researcher and they were instructed with games two times by a trained research staff: at the beginning of the training and after two weeks of training. Phone support, additional home visits, and guidance through the tablet computer were offered if required.	N	Per week, participants performed at least 3 balance gaming sessions (40 min each) and 3 muscle strength gaming sessions (15-20 min each)	Task challenges, such as narrowing base of support, adjusting speed of movement, increasing the number of repetitions, were increased	ICT-based iStoppFalls system; television, personal computer (Shuttle Barebone Slim-PC), Google TV set top box (STB) by Sony, a Microsoft Kinect (3D Depth sensor), a Senior Mobility Monitor (SMM) by Philips (3D accelerometer, barometer), Nexus 7 Android tablet	Y

Htut et al. 2018 [12] **Thailand**	Exercising with Xbox 360 games	N	Sessions were conducted by a physical therapist	Y	In 30 min session, participants played 6 games out of ten (Light Raise, Virtual Smash, Stack'em Up, One Ball Roll, Pin Push, Super Saver, Target Kick, Play Paddle Panic, Body Bally, Bamp Bash), games involved upper and lower limb and balance training	Participants progressed to advanced levels of each game when they obtained the highest score in a previous level	Xbox 360	N
Hughes et al. 2014 [13] **USA**	Exercising with Nintendo Wii in groups	N	Sessions were guided by interventionists	Y	After 10-15 min discussion of healthy aging topics, participants trained 60 min with "core" games (bowling, golf, tennis, baseball).	New games (e.g., Boom Blox, Wii Play, and Sports Resort) were added to the end of the session (final 15-30 min). "Wii tournaments" were held in weeks 10 and 20.	Nintendo Wii	N
Imam et al. 2017 [14] **Canada**	Exercising with Nintendo Wii Fit games in clinic and at home	N	In clinic, a trainer conducted sessions. During home sessions, participants' were contacted once a week by a trainer to monitor safety and equipment function.	N	During sessions, participants played yoga, balance, strength training and aerobic games.	Participants progressed to advanced levels of each game when they performed well in a previous level	Nintendo Wii, Nintendo Wii Balance Board	N
Jorgensen et al. 2013 [15] **Denmark**	Exercising with Nintendo Wii in pairs	N	Sessions were supervised by a trained physical therapist	Y	Participants played five balance games (table tilt, slalom ski, perfect 10, tight rope tension, penguin slide) for 2/3 of session's duration and muscle strengthening game (standing rowing squat) for 1/3 of the session's duration. Participants rotated between games and had 10 minute pauses.	NR	Nintendo Wii	N
Jung et al. 2015 [16] **Republic of Korea**	Exercising with Nintendo Wii Sport games	N	Participants got various visual and audio feedback and guidance from gaming system	Y	Participants played 3 games out of 4 (Wakeboard, Frisbee dog, Jet ski, Canoe game) on a unstable floor, a 2-minute break followed every 10 minutes	NR	Nintendo Wii	N
Karahan et al. 2015 [17] **Turkey**	Exercising with Xbox 360 Kinect Adventures, Sports and Sports Season 2 games	N	Games were instructed to participants by physicians, sessions were companied by an experienced nurse	Y	Participants played football, tennis, table tennis, skiing, golf, volleyball, and bowling games	NR	Xbox 360 Kinect, 46-inch LCD TV	N
Ku et al. 2019 [18] **Republic of Korea**	Exercising with the Kinect-designed specific games	N	Sessions were monitored by the research assistant	Y	Participants played the balloon game and cave game for exercising hip and knee flexion/extension, and rhythm game for enhancing one-leg standing ability	The research assistant adjusted training levels individually	Microsoft Kinect sensor, 3D environment displayed on a large	Y

							screen, personal computer	
Kwok & Pua 2016 [19] **Singapore**	Exercising with Nintendo Wii Active games, additional home balance and strengthening exercises	N	Sessions were guided and supervised by a physical therapist and a therapist assistant	Y	Participants played Wii Active games using balance board and resistance band. Exercising included cardiovascular, strengthening, calisthenics and balance training. Additionally balance and strengthening exercising was done at home on non-intervention days and during follow-up period	NR	Nintendo Wii, Nintendo Wii Balance Board	N
Lauzé et al. 2017 [20]**, Lauzé et al. 2018** [21] **Canada**	Exercising with Jintronix gaming system	N	Mainly at the beginning of intervention, a kinesiologist supervised 6 sessions, and other time was available for individual support over the phone or in person. Participants got various visual and audio feedback and guidance from gaming system	Y/N	Participants played according to individually tailored parameters. Session included warm-up period, aerobic, resistance and balance exercises, and cool-down period.	Individual degree of difficulty was adjusted by a kinesiologist according to the Web-portal reports	A computer and a TV screen or portable computer, Jintronix software, Microsoft Kinect, a TV screen	Y
Laver et al. 2012 [22] **Australia**	Exercising with Wii Fit games	N	Sessions were supervised by a physical therapist	Y	Participants played balance, strength and aerobic games while standing	NR	Nintendo Wii, Nintendo Wii Balance Board, wireless pointer	N
Lee & Shin 2013 [23] **Republic of Korea**	Exercising with PS2 EyeToy games in pairs	N	Sessions were guided and helped by a research assistant (exercise trainer). Participants got various visual and audio feedback and guidance from gaming system	Y	Participants had warm-up and cool-down periods and played six 2-3 minutes games (Wishi Washi: Window Washing, Keep Ups: Heading Game, Bowling, Bubble Pop, Boot Camp, and Kung Foo) that challenged balance, strength and aerobics. Participants were allowed to take a 5-min break after 3 games.	Participants started with 4 simple games for the first 2 weeks. From the third week, more challenging games (Kung Foo, Boot Camp) were added. Kung Foo game progressed to levels that are more difficult after participant completed previous stage.	PlayStation 2, Logitech motion-tracking camera, 25-inch liquid Crystal Display monitor	N
Lee et al. 2015 [24] **Republic of Korea**	Exercising with Xbox 360 games	N	A research assistant gave information on the exergame protocol on the first day of intervention. After that, research assistant supervised session, but did not interact with participants. Participants got various visual and audio feedback and guidance from gaming system	Y	Sessions included warm-up and cool-down exercises and games in where motions were based on tai chi. After 30 min of exercising, a 5-min break was given.	NR	Microsoft Kinect, Microsoft Xbox 360, a 1625.6mm monitor screen, Your Shape Fitness Evolved software	N

Lee et al. 2017 [25] **Republic of Korea**	Exercising with Wii Fit games in pairs	N	Sessions were monitored and instructed by six volunteer assistant, who also encourage participants to actively exergame. An avatar providing visual and auditory feedback while exergaming.	Y	Session included warm-up and cool-down periods, and six games (jogging for gait, swordplay for agility and balance, ski jump for balance, hula-hoop for balance and lower extremity strength, tennis for balance and agility, and step dance for gait and lower extremity strength) that were played competitively as circuit training.	NR	Nintendo Wii, Nintendo Wii Balance Board, Nintendo Wii joystick, a 42-inch LCD 3D TV, polarized glasses	N
Liao et al. [26] **2019 Taiwan**	Exercising with Kinect-designed specific games in groups	N	Sessions were supervised by an experienced physical therapist	Y	To improve balance, stability, strength and endurance, session included Tai Chi, resistance, and aerobic exercises, and functional and cognitive tasks that simulated daily activities	Virtual tasks got more challenging after participants completed the simpler tasks.	Microsoft Kinect, VR glasses	Y
Liao, Chen & Wang [27] **2019 Taiwan**	Exercising with Kinect-designed specific games in groups	N	Sessions were supervised by an experienced physical therapist	Y	Session included Tai Chi, resistance and aerobic exercises from PAPAMAMA program, and balance games (window cleaning, firework hitting, goldfish grasping), 20 minutes each.	Intensity was adjusted according to heart rate (50–75% of the maximal heart rate) and perceived exertion (13 to 14, equal to “somewhat hard”)	Microsoft Kinect, Tano and LongGood software packages, a screen (230 cm × 230 cm)	Y
Lim et al. 2017 [28] **Republic of Korea**	Combined or balance exercises with Wii Fit Plus games	N	Sessions were supervised by an experienced physical therapist, who at the first session instructed exergame protocol to participants.	Y	Session included warm-up period before exergaming that included balance, strength, flexibility, and endurance games or alternatively just balance games	NR	Nintendo Wii, Nintendo Wii Balance Board	N
Lin et al. [29] **2007 Taiwan**	Gamified proprioception exercises	N	Sessions were instructed by an experimenter, who provided verbal instructions and demonstrations	Y	Participants trained one leg at the time for 20 minutes, and had a 10-min break before training the other leg. Game included up-and-down and left-to-right movements that were controlled by the participant stepping onto pedals.	Games started with the slowest speed and progressed to faster speed after participants completed the slower tasks.	A personal computer, a colour computer screen, and a plantar control board (length and width: 57×57 cm, thick: 4cm, pedals: 8x9 cm)	Y
Maillot et al. 2012 [30] **France**	Exercising with Wii Fit games in pairs	N	Sessions were supervised by a physical trainer	Y	Session was divided into three periods in where participants played sport games that included tasks that required balance, stamina, cognitive judgment and combination of variety of skills. In first period participants played Tennis or Boxing game and Bowling game in three sessions, in second period Soccer Headers, Ski Jump and Marbles games, and in final period	Participants were advised to try to increase games' level of challenge and improve their performance during the intervention	Nintendo Wii, Nintendo Wii Remote and the Nunchuk, Nintendo Wii Balance Board	N

					Ski Slalom, Hula Hoop, Trampoline and Tennis Return of Serve.			
Maillot et al. 2014 [31] **France**	Exercising with Wii Fit games in pairs	N	NR	Y	Session was divided into two periods in where participants played sport games that included tasks that required balance and stamina. In first period, participants played Tennis or Boxing game, and in second period Soccer Headers, Ski Jump, Hula Hoop and Marbles games.	Participants were advised to try to increase games' level of challenge and improve their performance during the intervention	Nintendo Wii, Nintendo Wii Remote, Wii Nunchuk, Nintendo Wii Balance Board, a portable screen (76*102 cm)	N
Martel et al. 2018 [32] **Canada**	Exercising with Jintronix gaming system	N	A trained kinesiologist made six in-person supervision visits (sessions 1, 2, 4, 6, 12 and 18) and follow-up calls (weeks 4 and 8).	Y/N	Session included warm-up period, aerobic, strengthening and balance exercises, and cool-down period.	Individual degree of difficulty was adjusted by a kinesiologist according to the Web-portal reports	Jintronix software, Microsoft Kinect	Y
Micarelli et al. 2019 [33] **Italy**	Exercising with HMD games in addition to the Vestibular Rehabilitation	Y	At the beginning of protocol, participants were trained by an otoneurologist with expertise in HMD implementation.	N	Daily sessions included 20-minute exergaming while sitting on chair or sofa.	The trainers evaluated compliance, correct adjustments and performance twice a week in the clinic.	Track Speed Racing 3D game, the 5.2" display of a Windows Phone, the HMD 'Revelation' 3D VR Headset	N
Mirelman et al. 2016 [34] **Belgium, Israel, Italy, the Netherlands, and the UK**	Combined treadmill training with VR component	N	Session were supervised by a trainer. Participants got various visual and audio feedback and guidance from gaming system	Y	During session, participants walked on treadmill in computer simulated environment that included real-life challenges, consisting of obstacles, multiple pathways, and distractors that necessitated continual adjustment of steps.	Individualized progression was performed by adjusting treadmill's speed, duration of walking bouts, and size and frequency of the virtual obstacles and the distractors.	modified Microsoft Kinect, computer, large screen	Y
Monteiro-Junior et al. 2017 [35] **Brazil**	Exercising with Wii Fit games	N	Sessions were supervised by expert in sports medicine or physiotherapist	Y	In one session, the participant once played each of the following games: Rowing Squat, Penguim Slide, Basic Run Plus, Bump and Set, Heavy Bag, and Dance Basic 1.	NR	Nintendo Wii	N
Montero-Alía et al. 2019 [36] **Spain**	Exercising with Wii Fit games	N	Session were guided and managed by trained personnel. Participants got various visual and audio feedback and guidance from gaming system	Y	Participants played various balance exercises while standing barefoot on the balance board.	The personnel managed the sessions so that participants did all the exercises in each session for the time specified in the protocol. The number of repetitions varied for participants according to their agility.	Nintendo Wii, Nintendo Wii Balance Board	N

Morat et al. 2019 [37] **Germany**	Group exercising with Dividat Senso games under unstable conditions	N	A qualified study assistant guided sessions.	Y	The session included two to three pre-selected motor and cognitive games. The motor games in where the stepping was the main task were Objects, Shared, Simon, Flexi, Snake, Tetris, Habitats, Birds and Hexagon. Games with cognitive challenges were Ski and Rockect.	Progression was adjusted by increasing the degree of instability	Dividat Senso device (training platform 1.13 m*1.13 m with force sensors), screen combining Dividat Senso system with swinging Posturomed system	Y
Padala et al. 2012 [38] **USA**	Exercising with Wii Fit games	N	Session were guided by research personnel	Y	Sessions included warm-up and cool-down exercise (walk to and from room to gaming room), and strength, yoga, and balance games, 10 minutes each.	NR	Nintendo Wii, mobile television unit	N
Park et al. 2015 [39] **Republic of Korea**	Exercising with Wii Fit games	N	NR	Y	Sessions included training with Soccer Heading, Snowboard Slalom, and Table Tilt games, 10 minutes each.	NR	Nintendo Wii	N
Pichierri et al. 2012 [40] **Switzerland**	Resistance and balance training in groups and additional exercising with dancing game	Y	Sessions were supervised and conducted by the investigators	Y	Session included warm-up period (5 min), physical exercises (resistance training (25 min), balance exercises (10 min)) and video game dancing (10-15 min). In dancing, four 2-3 minutes song were played with a 30 seconds break after each song.	Progression was performed thru increasing number of repetitions and the load (weight vests) (physical exercises), and beats per minute and the difficulty level (video game dancing).	TX 6000 Metal DDR Platinum Pro, modification of the StepMania	N
Pitta et al. 2020 [41] **/ Santos et al. 2019** [42] **Brazil**	Vigorous exercising with Xbox 360 games	N	Sessions were guided by a qualified instructor guided who monitored exercise intensity and postures/movements during exergaming	Y	Session included following periods: warm-up (5 min), strength exercises (20 min), dynamic balance and cardiorespiratory exercises (10 min) and cool-down (5 min).	Progression was adjusted by increasing sets and repetitions of strength training (4 repetitions from 8 repetitions to 6 repetitions during the intervention period).	Microsoft Xbox 360, Microsoft Console, Kinect	N
Pluchino et al. 2012 [43] **USA**	Exercising with Wii Fit games	N	Participants got various visual and audio feedback and guidance from gaming system.	N	Session included warm-up (5 min), exercising with balance games (50 min) and cool-down (5-min).	Games started with easier levels of difficulty and progressed to advanced/higher levels after participants got maximum score of the level	Nintendo Wii, Nintendo Wii Balance Board	N
Ray et al. 2012 [44] **USA**	Exercising with Wii Fit games	N	Sessions were supervised by an assistant who supported participants ensuring their safety through gaming challenges	Y	Sessions included exercises using balance board and weighted vests.	Progression was adjusted by increasing weight of the vest every two weeks from 2 to 10 pound.	Nintendo Wii, Nintendo Wii Balance Board	N

Rendon et al. 2012 [45] **USA**	Exercising with Wii Fit games	N	Sessions were supervised by a physical therapist who assisted participants and ensured their safety during exergaming	Y	Session included warm-up and cool-down periods, and exercising with three games that included lunges, single leg extensions and twists. Game sequence was altered week-to-week during intervention. Participants were allowed to have resting periods between games.	NR	Nintendo Wii, Nintendo Wii Remote, Nintendo Wii Balance Board	N
Rutkowski et al. 2019 [46] **Poland**	Standard pulmonary rehabilitation in groups and additional exercising with Xbox 360 games	Y	A physiotherapist supervised sessions. Participants got instructions from gaming system.	Y	Exergaming part of the session included 15-30 minutes exercising with four Kinect Adventures games at a basic level. Gaming involved rafting, cross-country running, hitting a ball projected towards the player, and a roller-coaster ride.	The heart rate level of the exercise was measured and when the participant did not reach the heart rate specified for the exercise, the exercise was continued.	Microsoft Xbox 360, Kinect , a projector with speakers	N
Sajid et al. 2016 [47] **USA**	Exercising with Wii Fit games	N	Participants received one teaching session given by an exercise physiologist	N	Session included individually tailored exercise program using different exercises modules of game technology	Intensity of games were increased after participant demonstrated increase in physical performance	Nintendo Wii	N
Santamaria et al. 2018 [48] **Costa Rica**	Video game dancing in groups	N	Participants got instructions how to operate the video game.	Y	During session, participants danced 14 songs in random order at the beginner's level.	NR	Nintendo Dance Dance Revolution (DDR®), control mats in front of screen, Nintendo Wii console	N
Sato et al. 2015 [49] **Japan**	Exercising with Kinect-designed specific games	N	A physical therapist, a student, and game development staff operated sessions. Gaming system gave audio feedback to participants.	Y	Sessions included exergaming with Apple, Tightrope, Balloon popping and One-leg standing games	The games had different levels of difficulty.	Microsoft Kinect, Microsoft Kinect SDK version 1.5, Unity version 3.4.2, a three-dimensional (3D) support tool/engine used with Kinect.	Y
Schoene et al. 2013 [50] **Australia**	Exercising with stepping game	N	Participants was instructed and they got manual how to operate and play the stepping game. During intervention, participants were contacted four times by phone and they were able to contact research staff when they needed help.	N	Participants played stepping game, in where they synchronizing their stepping with instructions presented on the screen while listening the music they had selected. Music was not synchronized with the game.	Games started with easier levels of difficulty and progressed to advanced/higher levels after participants performed well at current level	Modified DDR Stepmania, computer, television	N

Schwenk et al. 2014 [51] **USA**	Exercising with specific balance games	N	A study coordinator, who gave instructions of balance tasks at the first session, supervised sessions. Participants got sensor-based feedback from the gaming system.	Y	Sessions included 6 blocks with 20 cycles of exercise tasks and three series of obstacle crossing with 15 repetitions each. Participants got one-minute break between successive blocks.	By the judgement of supervisor, progression was adjusted by moving to more advanced tasks and by increasing obstacle height.	a 24-inch computer screen, game-based virtual interface (MatLab®), Psych toolbox V2.54, 5 wearable inertial sensors (LegSys™)	Y
Schättin et al. 2016 [52] **Switzerland**	Exercising with specific Dividat games in groups	N	Session were supervised and instructed by three post graduate students.	Y	Session included warm-up and cool-down periods (5 min each), 20 minute exercising with four different games.	Progression was adjusted individually by training intensity that should achieve a moderate to vigorous training level and by increasing difficulty level of the games.	Impact Dance Platform (87.5 ×87.5× 2.5 cm), desktop computer, projector	y
Segura-Orti et al. 2019 [53] **Spain**	Exercising with Kinect-designed specific games	N	Before first session, participants had instruction and test session. A physical therapist monitored exergaming sessions.	Y	Sessions included warm-up and cool-down sessions, 5 minutes each. 30 minutes exergaming was held in 3 minutes bouts, rest period between bouts. Intensity was held between "somewhat hard" to "hard" (RPE 13-15/20).	Progression was adjusted by increasing the number of exercise bouts (from 1 to 10) and the difficulty of game. The physical therapist adjusted game-break periods and level of difficulty depending on the participant's performance.	standard computer, a TV, Microsofts Kinect, adapted version of ACT (A la Caza del Tesoro) program	N
Singh et al. 2013 [54] **Malaysia**	Exercising with Wii Fit games	N	NR	Y	Session included warm-up and cool-down periods, 5 min each, and 30 minutes exercising with games Ski Slalom, Table Tilt, Penguin Slide, Soccer Heading, Tight Rope Walk, Perfect 10 and Tilt City.	Games started with beginners level and progressed to advanced/expert levels after participants performed well at current level	Nintendo Wii, Nintendo Wii Balance Board	N
Smaerup et al. 2015 [55] **Denmark**	Rehabilitation training at hospital and exercising with specific Mitii games at home	Y	Participants got oral and written instructions of Mitii home exercises. During study period, game technology instructed exercises.	Y/N	Individualized sessions included drag-and-drop and follow-the-leader exercises aiming to enhance endurance, gaze stability, reflexes, smooth-pursuit eye movements and postural control	Once a month the physical therapist contacted participants to adjust progression by increasing duration, speed, and task challenges of games	Internet-connected computer, web camera connected to a cloud-based interactive training system using the Adobe Flash technology, headband	Y
Smaerup et al. 2016 [56] **Denmark**	Exercising with specific Mitii games at home	N	Game technology instructed exercises and registered the duration of exercising. The physical therapist followed duration and contacted	N	Daily sessions included drag-and-drop and follow-the-leader games played in standing position for 20-30 minutes.	NR	Internet-connected computer, web camera connected to a cloud-based interactive training system using the	Y

			participants if they had not trained for seven days.				Adobe Flash technology, headband	
Stanmore et al. 2019 [57] **UK**	Exercising with Kinect-designed specific games and falls prevention exercising following program leaflet	Y	The physiotherapist advised the participants. Sessions were supervised by a physiotherapist or physiotherapist's assistant	Y	Sessions included exercising with games that suited the participant's starting level of ability and usual falls prevention exercises	Progression was tailored over the 12 weeks by increasing number of games within session, game challenge and duration.	laptop, Microsoft Kinect	Y
Sutanto et al. 2019 [58] **Indonesia**	Outpatient exercising program and exercising with Wii Fit program	Y	Supervised session with one-to-one exergaming instruction	Y	Session included 30 min cycle exercise training at intensity of 5 on modified 10-point Borg scale and 30 min exergaming with Yoga deep breathing, Yoga half-moon, Torso twist and Free run games.	NR	Nintendo Wii, Nintendo Wii Balance Board, flatscreen TV	N
Szturm et al. 2011 [59] **Canada**	Exercising with specific video games	N	NR	Y	Sessions included exercising with three games (Under Pressure, Memory Match and Balloon Burst) by making horizontal or vertical motions while standing on pressure mat.	Progression was adjusted individually by increasing movement amplitude, game speed, game task precision, and exercise duration.	FSA pressure mat, FSA interface box, laptop computer	Y
Tollar et al. 2019 [60] **Hungary**	Exercising with Xbox 360 games	N	Sessions were delivered by physical therapists who were trained and supervised by the principal investigator	Y	Sessions included warm-up and cool-down, 5 min each, and exergaming with three gaming modules (Reflex Ridge, Space Pop, Just Dance), 15 min each. Participants were allowed to have 5 min rest.	Training intensity was targeted to be 80% of maximum HR. When HR deviated ±5% from target, the Polar monitor gave feedback to participant.	Xbox 360	N
Toulotte et al. 2012 [61] **France**	Exercising with Wii Fit games	N	NR	Y	Games, such as heading soccer, ski jumping, yoga, downhill skiing, game balls and tightrope walker, were used for training, a chair in front of participant for safety.	Progression was adjusted individually with game levels	Nintendo Wii	N
Tsang & Fu 2016 [62] **China**	Exercising with the Wii Fit balance games	N	NR	Y	The Wii Fit balance training games included Soccer Heading, Table Tilt, and Balance Bubble.	NR	Nintendo Wii, Nintendo Wii Balance Board	N
Uzor & Baillie 2019 [63] **England**	Exercising with tailored exergame system in addition to standard care	N	Research assistant made home visit to ensure a safe environment and train participants to exergames	N	Participants trained with six exergames for strength (Pigeon Express, Horse Hurdles, Fire Rescue) and balance (River Gems, Panda Peak, Snow Flags).	Progression was adjusted by three levels of game difficulty (easy, normal, difficult).	2 IMU sensors, laptop computer, Recov-R software	Y

Villumsen et al. 2019 [64] **Denmark**	Aerobic and strength exercises with Xbox360 Sport and Adventure games	N	A physical therapist gave individual 90 min instruction before home training exergaming	N	Sessions included warm-up and cool-down period and aerobic and strength exercises by games.	To gradually increase intensity, use of free weights (0.5, 1.0 and 2.0 kg) were added to exergaming program	Microsoft Xbox 360 Kinect	N
Yeşilyaprak et al. 2016 [65] **Turkey**	Balance training with the VR rehabilitation system	N	Sessions were provided by a trained physical therapist. Participants followed visual and audio feedback of gaming system.	Y	Session included exergames for warm-up (5 min), training (35-45 min) and cool-down (5 min)	Progression was adjusted by closing eyes while gaming, and by reducing base of support and increasing speed, duration and challenge of games.	BTS NIRVANA VR Interactive System	Y
Yuen et al. 2019 [66] **USA**	Exercising with Wii Fit games	N	To support of participants, research assistant contacted them week after baseline assessment and once a month during intervention	N	Session included exergaming with intensity of moderate to heavy (3 to 5 on 10-point Borg scale)	NR	Nintendo Wii U, Nintendo Balance board	N
Y = Yes, N = No, NR = Not reported								

Figure C1. Risk of bias in studies (n=66) included in the review: (A) Randomization process, (B) Deviations from the intended interventions, (C) Missing outcome data, (D) Measurement of the outcome, (E) Selection of the reported results, (F) Overall.

	Risk of Bias					
Study or Subgroup	A	B	C	D	E	F
Bacha et al. 2018	+	+	+	+	?	?
Bieryla & Dold 2013	?	−	+	?	?	−
Bieryla 2016	?	?	+	?	?	?
Chow & Mann2015	?	?	+	?	?	?
Christiansen et al. 2015	+	+	+	+	?	?
Daniel 2012	−	−	+	?	?	−
Delbroek et al. 2017	?	?	+	+	?	?
Eggenberger et al. 2015	?	+	+	?	?	?
Fung et al. 2012	+	+	+	+	+	+
Gomes et al. 2018	+	+	+	+	?	?
Gschwind et al. 2015	+	?	+	+	+	?
Htut et al. 2018	+	+	+	+	?	?
Hughes et al. 2014	?	?	+	?	?	?
Imam et al. 2017	+	?	+	+	?	?
Jorgensen et al. 2013	+	−	+	+	?	−
Jung et al. 2015	?	?	+	?	?	?
Karahan et al. 2015	+	?	+	?	?	?
Ku et al. 2019	+	?	+	+	?	?
Kwok & Pua 2016	+	?	+	+	+	?
Lauze et al. 2017	+	−	+	?	?	−
Lauze et al. 2018	+	−	+	?	?	−
Laver et al. 2012	+	+	+	+	?	?
Lee et al. 2013	?	?	+	?	?	?
Lee et al. 2015	+	−	+	+	?	−
Lee et al. 2017	+	?	+	+	?	?
Liao et al. 2019	+	?	+	+	?	?
Liao, Chen & Wang 2019	+	+	+	+	?	?
Lim et al. 2017	?	?	+	?	?	?
Lin et al. 2007	?	?	+	?	?	?
Maillot et al. 2012	?	?	+	?	?	?
Maillot et al. 2014	+	?	+	+	?	?
Martel et al. 2018	?	?	+	?	?	?
Micarelli et al. 2019	?	+	+	?	?	?
Mirelman et al. 2016	+	+	+	+	+	+
MonteiroJunior et al.2017	+	+	+	?	?	?
Montero-Alia et al. 2019	−	−	−	?	+	−
Morat et al. 2019	+	?	+	?	?	?
Padala et al. 2012	?	?	+	?	?	?
Park et al. 2015	?	?	+	?	?	?
Pichierri et al. 2012	+	−	?	+	?	−
Pitta et al. 2019	+	?	+	+	?	?
Pluchino et al. 2012	+	−	+	?	?	−
Ray et al. 2012	−	−	−	?	?	−
Rendon et al. 2012	?	?	+	+	?	?
Rutkowski et al. 2019	−	−	−	?	+	−
Sajid et al. 2016	−	?	+	+	−	−
Santamaria et al. 2018	?	?	+	?	?	?
Santos et al. 2019	?	−	+	?	?	−
Sato et al. 2015	+	?	+	+	?	?
Schoene et al. 2013	+	?	+	+	?	?
Schwenk et al. 2014	+	+	+	+	?	?
Schättin et al. 2016	+	+	+	+	?	?
Segura-Orti et al. 2019	+	?	+	+	−	−
Singh et al. 2013	?	?	+	+	?	?
Smaerup et al. 2015	+	?	+	?	−	−
Smaerup et al. 2016	+	?	+	?	?	?
Stanmore et al. 2019	?	+	+	?	?	?
Sutanto et al. 2019	?	?	+	?	+	?
Szturm et al. 2011	?	+	+	+	?	?
Tollar et al. 2019	?	+	+	+	?	?
Toulotte et al. 2012	+	+	+	?	?	?
Tsang & Fu 2016	?	?	+	?	?	?
Uzor & Baillie 2019	+	−	−	+	?	−
Villumsen et al. 2019	+	?	+	+	+	?
Yesilyaprak et al. 2016	?	?	+	+	?	?
Yuen et al. 2019	?	+	+	+	?	?

Figure C2. Summary of risk of bias across RCTs (n=58) included in meta-analysis.

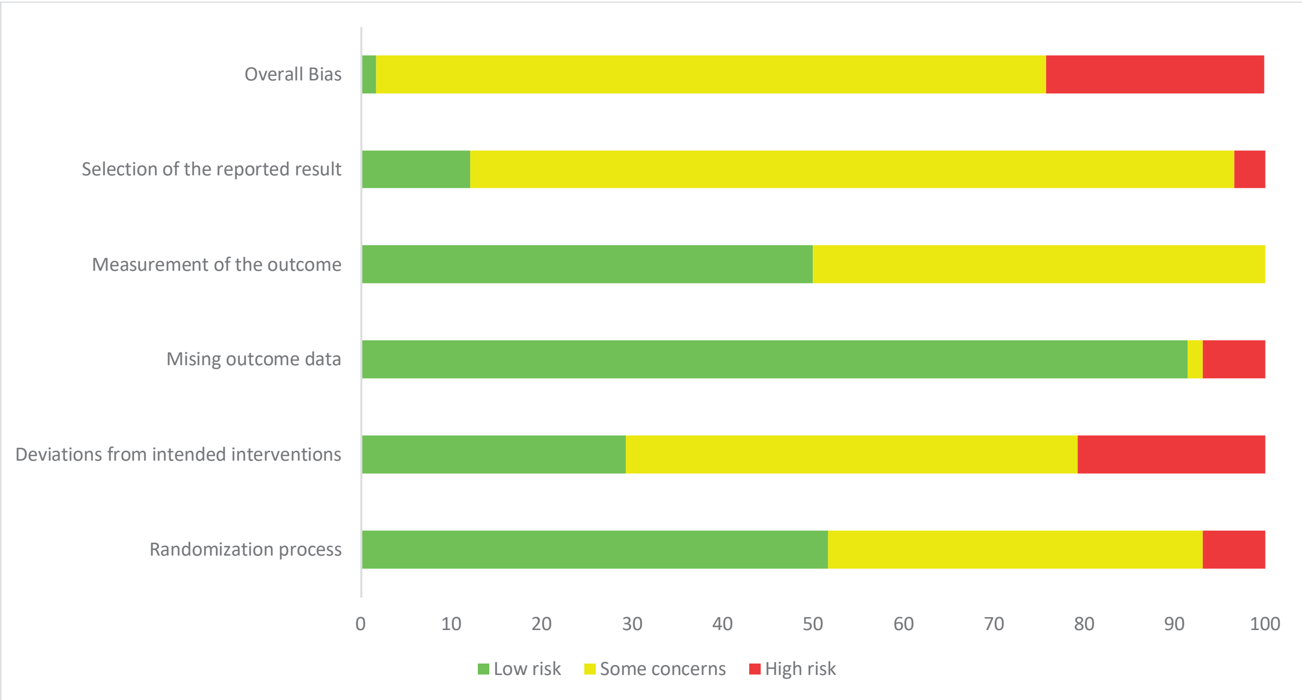

Table C3. Summary of Findings

Exergaming intervention compared to comparison group intervention[3]

Patients or population: Older adults aged 60 years or older with no common neurological condition
Settings: Varies
Intervention: Exergaming
Comparison: Other exercising protocol (other exergaming, other exercising, cognitive training) and no exercising protocol (control), i.e. active and inactive control respectively

Outcomes	SMD with 95% Confidence Interval Heterogeneity (I^2, p)	No of studies with high overall risk of bias[2]	No of Participants (Studies)	Publication bias[5]	Certainty of the evidence (GRADE)	Comments
Walking post intervention	-0.21 [-0.36, -0.06] 76.3%, <.0001	14	3102 (58)	Not serious	⊕⊕⊕◯Moderate[1]	Walking was assessed with validated and standardized meters (Timed Up & Go test, walking speed test, 2- and 6-minute walking test, Dynamic Gait Index, Functional Gait Assessment, Tinetti's Gait).
Walking post follow-up	-0.32 [-0.64, 0.00] 72.8%, <.0001	4	1028 (13)	Not serious	⊕⊕◯◯Low[14]	Walking was assessed with validated and standardized meters (Timed Up & Go test, walking speed test, 2-minute walking test, Functional Gait Assessment and Tinetti's Gait).

[1] Downgrading by one level due to inconsistency: Substantial heterogeneity.

[2] No downgrading due to risk of bias, as meta-regression analysis did not revealed significant association when high risk of bias was assessed by domains. In studies post intervention, high risk of bias was identified in randomization process (4), deviations from intended intervention (12), missing outcome data (4) and selection of the reported results (2). In studies post follow-up, high risk of bias was identified in randomization process (1), deviations from intended intervention (4) and missing outcome data (1).

[3] No downgrading due to indirectness; Correspondence to review's PICO criteria.

[4] Downgrading by one level due to imprecision: Wide confidence interval including null effect and small amount of studies.

[5] No downgrading due to publication bias: Asymmetry in the funnel plots indicated possibility of publication bias, but studies in favor of both groups has been published equally.

REFERENCES

1. Bacha J, Gomes G, De Freitas T, et al. Effects of kinect adventures games versus conventional physical therapy on postural control in elderly people: A randomized controlled trial. *Games Health J*. 2018;7:24-36. doi:10.1089/g4h.2017.0065

2. Bieryla KA, Dold NM. Feasibility of Wii Fit training to improve clinical measures of balance in older adults. *Clin Interv Aging*. 2013;8:775-781. doi:10.2147/CIA.S46164

3. Bieryla KA. Xbox Kinect training to improve clinical measures of balance in older adults: A pilot study. *Aging Clin Exp Res*. 2016;28:451-457. doi:10.1007/s40520-015-0452-y

4. Chow DHK, Mann SKF. Effect of cyber-golfing on balance amongst the elderly in Hong Kong: A pilot randomised trial. *Hong Kong J Occup Ther*. 2015;26:9-13. doi:10.1016/j.hkjot.2015.08.001

5. Christiansen CL, Bade MJ, Davidson BS, Dayton MR, Stevens-Lapsley JE. Effects of weight-bearing biofeedback training on functional movement patterns following total knee arthroplasty: A randomized controlled trial. *J Orthop Sports Phys Ther*. 2015;45:647-655. doi:10.2519/jospt.2015.5593

6. Daniel K. Wii-hab for pre-frail older adults. *Rehabil Nurs*. 2012;37:195-201. doi:10.1002/rnj.25

7. Delbroek T, Vermeylen W, Spildooren J. The effect of cognitive-motor dual task training with the biorescue force platform on cognition, balance and dual task performance in institutionalized older adults: a randomized controlled trial. *J Phys Ther Sci*. 2017;29:1137-1143. doi:10.1589/jpts.29.1137

8. Eggenberger P, Theill N, Holenstein S, Schumacher V, de Bruin ED. Multicomponent physical exercise with simultaneous cognitive training to enhance dual-task walking of older adults: A secondary analysis of a 6-month randomized controlled trial with I-year follow-up. *Clin Interv Aging*. 2015;10:1711-1732. doi:10.2147/CIA.S91997

9. Fung V, Ho A, Shaffer J, Chung E, Gomez M. Use of Nintendo Wii FitTM in the rehabilitation of outpatients following total knee replacement: A preliminary randomised controlled trial. *Physiotherapy*. 2012;98:183-188. doi:10.1016/j.physio.2012.04.001

10. Gomes GCV, Simoes M do S, Lin SM, et al. Feasibility, safety, acceptability, and functional outcomes of playing Nintendo Wii Fit PlusTM for frail older adults: A randomized feasibility clinical trial. *Maturitas*. 2018;118:20-28. doi:10.1016/j.maturitas.2018.10.002

11. Gschwind YJ, Eichberg S, Ejupi A, et al. ICT-based system to predict and prevent falls (iStoppFalls): Results from an international multicenter randomized controlled trial. *Eur Rev Aging Phys Act*. 2015;12:1-11. doi:10.1186/s11556-015-0155-6

12. Htut TZC, Hiengkaew V, Jalayondeja C, Vongsirinavarat M. Effects of physical, virtual reality-based, and brain exercise on physical, cognition, and preference in older persons: A randomized controlled trial. *Eur Rev Aging Phys Act*. 2018;15:1-12. doi:10.1186/s11556-018-0199-5

13. Hughes TF, Flatt JD, Fu B, Butters MA, Chang CCH, Ganguli M. Interactive video gaming compared with health education in older adults with mild cognitive impairment: A feasibility study. *Int J Geriatr Psychiatry*. 2014;29:890-898. doi:10.1002/gps.4075

14. Imam B, Miller WC, Finlayson H, Eng JJ, Jarus T. A randomized controlled trial to evaluate the feasibility of the Wii Fit for improving walking in older adults with lower limb amputation. *Clin Rehabil*. 2017;31:82-92. doi:10.1177/0269215515623601

15. Jorgensen MG, Laessoe U, Hendriksen C, Nielsen OBF, Aagaard P. Efficacy of nintendo wii training on mechanical leg muscle function and postural balance in community-dwelling older adults: A randomized controlled trial. *Journals Gerontol - Ser A Biol Sci Med Sci*. 2013;68:845-852. doi:10.1093/gerona/gls222

16. Jung DI, Ko DS, Jeong MA. Kinematic effect of Nintendo Wii™ sports program exercise on obstacle gait in elderly women with falling risk. *J Phys Ther Sci*. 2015;27:1397-1400. doi:10.1589/jpts.27.1397

17. Karahan AY, Tok F, Taşkın H, Küçüksaraç S, Başaran A, Yildirim P. Effects of exergames on balance, functional mobility, and quality of life of geriatrics versus home exercise programme: Randomized controlled study. *Cent Eur J Public Health*. 2015;23:S14-S18. doi:10.21101/cejph.a4081

18. Ku J, Kim YJ, Cho S, Lim T, Lee HS, Kang YJ. Three-dimensional augmented reality system for balance and mobility rehabilitation in the elderly: A randomized controlled trial. *Cyberpsychology, Behav Soc Netw*. 2019;22:132-141. doi:10.1089/cyber.2018.0261

19. Kwok BC, Pua YH. Effects of Wii Active exercises on fear of falling and functional outcomes in community-dwelling older adults: A randomised control trial. *Age Ageing*. 2016;45:621-627. doi:10.1093/ageing/afw108

20. Lauzé M, Martel D, Aubertin-Leheudre M. Feasibility and effects of a physical activity program using gerontechnology in assisted living communities for Older Adults. *J Am Med Dir Assoc*. 2017;18:1069-1075. doi:10.1016/j.jamda.2017.06.030

21. Lauzé M, Martel D, Agnoux A, et al. Feasibility, acceptability and effects of a home-based exercise program using a gerontechnology on physical capacities after a minor injury in community-living older adults: A pilot study. *J Nutr Heal Aging*. 2018;22:16-25. doi:10.1007/s12603-017-0938-8

22. Laver K, George S, Ratcliffe J, et al. Use of an interactive video gaming program compared with conventional physiotherapy for hospitalised older adults: A feasibility trial. *Disabil Rehabil*. 2012;34:1802-1808. doi:10.3109/09638288.2012.662570

23. Lee S, Shin S. Effectiveness of virtual reality using video gaming technology in elderly adults with diabetes mellitus. *Diabetes Technol Ther*. 2013;15:489-496. doi:10.1089/dia.2013.0050

24. Lee M, Son J, Kim J, Yoon BC. Individualized feedback-based virtual reality exercise improves older women's self-perceived health: A randomized controlled trial. *Arch Gerontol Geriatr*. 2015;61:154-160. doi:10.1016/j.archger.2015.06.010

25. Lee Y, Choi W, Lee K, Song C, Lee S. Virtual reality training with three-dimensional video games improves postural balance and lower extremity strength in community-dwelling older adults. *J Aging Phys Act*. 2017;25:621-627. doi:10.1123/japa.2015-0271

26. Liao Y-Y, Chen I-H, Lin Y-J, Chen Y, Hsu W-C. Effects of virtual reality-based physical and cognitive training on executive function and dual-task gait performance in older adults with mild cognitive impairment: A randomized control trial. *Front Aging Neurosci*. 2019;11:1-10. doi:10.3389/fnagi.2019.00162

27. Liao Y-Y, Chen I-H, Wang R-Y. Effects of Kinect-based exergaming on frailty status and physical performance in prefrail and frail elderly: A randomized controlled trial. *Sci Rep*. 2019;9:1-9. doi:10.1038/s41598-019-45767-y

28. Lim J, Cho JJ, Kim J, Kim Y, Yoon BC. Design of virtual reality training program for prevention of falling in the elderly: A pilot study on complex versus balance exercises. *Eur J Integr Med*. 2017;15:64-67. doi:10.1016/j.eujim.2017.09.008

29. Lin DH, Lin YF, Chai HM, Han YC, Jan MH. Comparison of proprioceptive functions between computerized proprioception facilitation exercise and closed kinetic chain exercise in patients with knee osteoarthritis. *Clin Rheumatol*. 2007;26:520-528. doi:10.1007/s10067-006-0324-0

30. Maillot P, Perrot A, Hartley A. Effects of interactive physical-activity video-game training on physical and cognitive function in older adults. *Psychol Aging*. 2012;27:589-600. doi:10.1037/a0026268

31. Maillot P, Perrot A, Hartley A, Do MC. The braking force in walking: Age-related differences and improvement in older adults with exergame training. *J Aging Phys Act*. 2014;22:518-526. doi:10.1123/JAPA.2013-0001

32. Martel D, Lauzé M, Agnoux A, et al. Comparing the effects of a home-based exercise program using a gerontechnology to a community-based group exercise program on functional capacities in older adults after a minor injury. *Exp Gerontol*. 2018;108:41-47. doi:10.1016/j.exger.2018.03.016

33. Micarelli A, Viziano A, Micarelli B, Augimeri I, Alessandrini M. Vestibular rehabilitation in older adults with and without mild cognitive impairment: Effects of virtual reality using a head-mounted display. *Arch Gerontol Geriatr*. 2019;83:246-256. doi:10.1016/j.archger.2019.05.008

34. Mirelman A, Rochester L, Maidan I, et al. Addition of a non-immersive virtual reality component to treadmill training to reduce fall risk in older adults (V-TIME): A randomised controlled trial. *Lancet*. 2016;388:1170-1182. doi:10.1016/S0140-6736(16)31325-3

35. Monteiro-Junior RS, Figueiredo LFDS, Maciel-Pinheiro PDT, et al. Virtual reality–based physical exercise with exergames (PhysEx) improves mental and physical health of institutionalized older adults. *J Am Med Dir Assoc*. 2017;18:454.e1-454.e9. doi:10.1016/j.jamda.2017.01.001

36. Montero-Alía P, Miralles-Basseda R, López-Jiménez T, et al. Controlled trial of balance training using a video game console in community-dwelling older adults. *Age Ageing*. 2019;48:506-512. doi:10.1093/ageing/afz047

37. Morat M, Bakker J, Hammes V, et al. Effects of stepping exergames under stable versus unstable conditions on balance and strength in healthy community-dwelling older adults: A three-armed randomized controlled trial. *Exp Gerontol*. 2019;127:110719. doi:10.1016/j.exger.2019.110719

38. Padala KP, Padala PR, Malloy TR, et al. Wii-fit for improving gait and balance in an assisted living facility: A pilot study. *J Aging Res*. 2012;2012. doi:10.1155/2012/597573

39. Park EC, Kim SG, Lee CW. The effects of virtual reality game exercise on balance and gait of the elderly. *J Phys Ther Sci*. 2015;27:1157-1159. doi:10.1589/jpts.27.1157

40. Pichierri G, Murer K, de Bruin ED. A cognitive-motor intervention using a dance video game to enhance foot placement accuracy and gait under dual task conditions in older adults: A randomized controlled trial. *BMC Geriatr*. 2012;12:74. doi:10.1186/1471-2318-12-74

41. Pitta A, Pereira G, Lara JPR, et al. The Effects of Different Exergame Intensity Training on Walking Speed in Older Women. *Games Health J*. 2020;9:121-128. doi:10.1089/g4h.2019.0109

42. Santos GOR, Wolf R, Silva MM, Rodacki ALF, Pereira G. Does exercise intensity increment in exergame promote changes in strength, functional capacity and perceptual parameters in pre-frail older women? A randomized controlled trial. *Exp Gerontol*. 2019;116:25-30. doi:10.1016/j.exger.2018.12.009

43. Pluchino A, Lee SY, Asfour S, Roos BA, Signorile JF. Pilot study comparing changes in postural control after training using a video game balance board program and 2 standard activity-based balance intervention programs. *Arch Phys Med Rehabil*. 2012;93:1138-1146. doi:10.1016/j.apmr.2012.01.023

44. Ray C, Melton F, Ramirez R, Keller D. The effects of a 15-week exercise intervention on fitness and postural control in older adults. *Act Adapt Aging*. 2012;36:227-241. doi:10.1080/01924788.2012.696236

45. Rendon AA, Lohman EB, Thorpe D, Johnson EG, Medina E, Bradley B. The effect of virtual reality gaming on dynamic balance in older adults. *Age Ageing*. 2012;41:549-552. doi:10.1093/ageing/afs053

46. Rutkowski S, Rutkowska A, Jastrzebski D, Racheniuk H, Pawelczyk W, Szczegielniak J. Effect of virtual reality-based rehabilitation on physical fitness in patients with chronic obstructive pulmonary disease. *J Hum Kinet*. 2019;69:149-157. doi:10.2478/hukin-2019-0022

47. Sajid S, Dale W, Mustian K, et al. Novel physical activity interventions for older patients with prostate cancer on hormone therapy: A pilot randomized study. *J Geriatr Oncol*. 2016;7:71-80. doi:10.1016/j.jgo.2016.02.002

48. Santamaría KG, Fonseca AS, Jiménez JM, Mora LCS. Balance, attention and concentration improvements following an exergame training program in elderly. *Retos-Nuevas Tendencias En Educ Fis Deport Y Recreacion*. 2018;2041:102-105.

49. Sato K, Kuroki K, Saiki S, Nagatomi R. Improving walking, muscle strength, and balance in the elderly with an exergame using kinect: A randomized controlled trial. *Games Health J*. 2015;4:161-167. doi:10.1089/g4h.2014.0057

50. Schoene D, Lord SR, Delbaere K, Severino C, Davies TA, Smith ST. A randomized controlled pilot study of home-based step training in older people using videogame technology. *PLoS One*. 2013;8:e57734-e57734. doi:10.1371/journal.pone.0057734

51. Schwenk M, Grewal GS, Honarvar B, et al. Interactive balance training integrating sensor-based visual feedback of movement performance: A pilot study in older adults. *J*

Neuroeng Rehabil. 2014;11:164. doi:10.1186/1743-0003-11-164

52. Schättin A, Arner R, Gennaro F, de Bruin ED. Adaptations of prefrontal brain activity, executive functions, and gait in healthy elderly following exergame and balance training: A randomized-controlled study. *Front Aging Neurosci*. 2016;8. doi:10.3389/fnagi.2016.00278

53. Segura-Ortí E, Pérez-Domínguez B, Ortega-Pérez de Villar L, et al. Virtual reality exercise intradialysis to improve physical function: A feasibility randomized trial. *Scand J Med Sci Sport*. 2019;29:89-94. doi:10.1111/sms.13304

54. Singh DKA, Rajaratnam BS, Palaniswamy V, Raman VP, Bong PS, Pearson H. Effects of balance-focused interactive games compared to therapeutic balance classes for older women. *Climacteric*. 2013;16:141-146. doi:10.3109/13697137.2012.664832

55. Smaerup M, Grönvall E, Larsen SB, Laessoe U, Henriksen J-J, Damsgaard EM. Computer-assisted training as a complement in rehabilitation of patients with chronic vestibular dizziness: A randomized controlled trial. *Arch Phys Med Rehabil*. 2015;96:395-401. doi:10.1016/j.apmr.2014.10.005

56. Smaerup M, Laessoe U, Grönvall E, Henriksen JJ, Damsgaard EM. The use of computer-assisted home exercises to preserve physical function after a vestibular rehabilitation program: A randomized controlled study. *Rehabil Res Pract*. 2016;2016. doi:10.1155/2016/7026317

57. Stanmore EK, Mavroeidi A, de Jong LD, et al. The effectiveness and cost-effectiveness of strength and balance Exergames to reduce falls risk for people aged 55 years and older in UK assisted living facilities: A multi-centre, cluster randomised controlled trial. *BMC Med*. 2019;17:49. doi:10.1186/s12916-019-1278-9

58. Sutanto YS, Makhabah DN, Aphridasari J, Doewes M, Suradi AN. Videogame assisted exercise training in patients with chronic obstructive pulmonary disease: A preliminary study. *Pulmonology*. 2019;25:275-282. doi:10.1016/j.pulmoe.2019.03.007

59. Szturm T, Betker AL, Moussavi Z, Desai A, Goodman V. Effects of an interactive computer game exercise regimen on balance impairment in frail community-dwelling older adults: A randomized controlled trial. *Phys Ther*. 2011;91:1449-1462. doi:10.2522/ptj.20090205

60. Tollar J, Nagy F, Moizs M, Toth BE, Sanders LMJ, Hortobagyi T. Diverse exercises similarly reduce older adults' mobility limitations. *Med Sci Sports Exerc*. 2019;51:1809-1816. doi:10.1249/MSS.0000000000002001

61. Toulotte C, Toursel C, Olivier N. Wii Fit (R) training vs. adapted physical activities: Which one is the most appropriate to improve the balance of independent senior subjects? A randomized controlled study. *Clin Rehabil*. 2012;26:827-835. doi:10.1177/0269215511434996

62. Tsang WWN, Fu ASN. Virtual reality exercise to improve balance control in older adults at risk of falling. *Hong Kong Med J*. 2016;22:S19-S22.

63. Uzor S, Baillie L. Recov-R: Evaluation of a home-based tailored exergame system to reduce fall risk in seniors. *Acm Trans Comput Interact*. 2019;26. doi:10.1145/3325280

64. Villumsen BR, Jorgensen MG, Frystyk J, Hørdam B, Borre M. Home-based 'exergaming' was safe and significantly improved 6-min walking distance in patients

with prostate cancer: A single-blinded randomised controlled trial. *BJU Int*. 2019;124:600-608. doi:10.1111/bju.14782

65. Yeşilyaprak SS, Yildirim MŞ, Tomruk M, Ertekin Ö, Algun ZC. Comparison of the effects of virtual reality-based balance exercises and conventional exercises on balance and fall risk in older adults living in nursing homes in Turkey. *Physiother Theory Pract*. 2016;32:191-201. doi:10.3109/09593985.2015.1138009

66. Yuen HK, Lowman JD, Oster RA, de Andrade JA. Home-based pulmonary rehabilitation for patients with idiopathic pulmonary fibrosis: A pilot study. *J Cardiopulm Rehabil Prev*. 2019;39:281-284. doi:10.1097/HCR.0000000000000418

III

EFFECTS OF A HOME-BASED, EXERGAMING INTERVENTION ON PHYSICAL FUNCTION AND PAIN AFTER TOTAL KNEE REPLACEMENT IN OLDER ADULTS: A RANDOMIZED CONTROLLED TRIAL

by

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BMJ Open Sport & Exercise Medicine 9 (e001416), 1–9

https://doi.org/10.1136/bmjsem-2022-001416

BMJ Open Sport & Exercise Medicine

Effects of a home-based, exergaming intervention on physical function and pain after total knee replacement in older adults: a randomised controlled trial

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To cite: Janhunen M, Katajapuu N, Paloneva J, *et al*. Effects of a home-based, exergaming intervention on physical function and pain after total knee replacement in older adults: a randomised controlled trial. *BMJ Open Sport & Exercise Medicine* 2023;**9**:e001416. doi:10.1136/bmjsem-2022-001416

► Additional supplemental material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/bmjsem-2022-001416).

Accepted 15 February 2023

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ABSTRACT

Objectives To investigate the effects of 4 months of customised, home-based exergaming on physical function and pain after total knee replacement (TKR) compared with standard exercise protocol.

Methods In this non-blinded randomised controlled trial, 52 individuals aged 60–75 years undergoing TKR were randomised into an exergaming (intervention group, IG) or a standard exercising group (control group, CG). Primary outcomes were physical function and pain measured before and after (2 months and 4 months) surgery using the Oxford Knee Score (OKS) and Timed Up and Go (TUG) test. Secondary outcomes included measures of the Visual Analogue Scale, 10m walking, short physical performance battery, isometric knee extension and flexion force, knee range of movement and satisfaction with the operated knee.

Results Improvement in mobility measured by TUG was greater in the IG (n=21) at 2 (p=0.019) and 4 months (p=0.040) than in the CG (n=25). The TUG improved in the IG by −1.9 s (95% CI, −2.9 to −1.0), while it changed by −0.6 s (95% CI −1.4 to 0.3) in the CG. There were no differences between the groups in the OKS or secondary outcomes over 4 months. 100% of patients in the IG and 74% in the CG were satisfied with the operated knee.

Conclusion In patients who have undergone TKR, training at home with customised exergames was more effective in mobility and early satisfaction and as effective as standard exercise in pain and other physical functions. In both groups, knee-related function and pain improvement can be considered clinically meaningful.

Trial registration number NCT03717727.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Gamified exercising, that is, exergaming, has proven to improve physical outcomes in older adults. However, little is known about its effects on physical function and pain in rehabilitation in aged surgical patients.

WHAT THIS STUDY ADDS

⇒ Home-based exergaming after total knee replacement (TKR) surgery was more effective on mobility than standard post-TKR exercise.

⇒ Patients who underwent gamified rehabilitation were more satisfied with the operated knee than those who did standard exercising.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Although exergaming was not superior to the standard protocol, it could be used in physical function and pain management in rehabilitation after TKR.

INTRODUCTION

Total knee replacement (TKR) is a surgical treatment for severe knee osteoarthritis (OA). To maximise the individual benefits of TKR surgery, it is important to offer rehabilitation protocols that have the potential to improve compliance in home-based rehabilitation and thus have a beneficial effect on the postoperative outcomes.[1–3] One such novel protocol is rehabilitation using exergames.[4]

In physical rehabilitative exergames, therapeutic exercise is exploited using computer games controlled through the player's bodily movements or reactions. Exergames may be tailored to the therapeutic exercises of a specific group of patients,[5] taking into account the progression of the rehabilitation process.[6] Moreover, exergames may be implemented at a person's home with self-directed rehabilitation,[7] for which there is a growing need in situations where the increased demand for rehabilitation is unmet due to, for example, long distances or restrictions imposed by the pandemic.

The effects of exergaming have been studied in older adults and have shown promising results in improving physical outcomes.[4 8 9] However, few studies have evaluated the effectiveness of exergames in aged surgical patients, such as those with TKR.[10–12] More research is needed to strengthen the evidence on the effect of exergames used as therapeutic exercises after TKR surgery, especially when performed self-directedly with customised exercises at home.[13 14] Therefore, this randomised controlled trial (RCT) aimed to investigate whether home-based exercise with custom exergames for post-TKR rehabilitation is effective for physical function and pain reduction in older adults after TKR surgery compared with home exercise using a standard protocol.

METHODS

Trial design

This study was a 4-month non-blinded, dual-centre RCT with parallel groups (allocation ratio 1:1) comparing unsupervised exergame-based home exercise (intervention group, IG) with unsupervised home exercise by standard protocol (control group, CG) after TKR surgery in older adults. The study was conducted using the same protocol in Finland's Southwest and Central Finland Healthcare Districts.

Knee-related pain and physical function, including knee-related function, mobility, walking and lower extremity performance and strength, were assessed using several measurements. Measurements were performed before (baseline) and after (2-month and 4-month follow-up) TKR surgery in the exercise laboratory, according to the patients' residential area. Baseline assessment was performed within 2 weeks before the day of surgery, and 2-month and 4-month follow-up assessments were performed within ±5 days from the time point calculated according to the day of surgery. Trained physical therapists completed assessments of individual participants.

During the year 2020, the COVID-19 pandemic caused unavoidable situations in the study; the number of elective surgeries decreased, hospitals and laboratories had lockdowns, and some felt that coming to follow-up assessments at the exercise laboratory could pose a high risk of developing the disease. Recruitment slowed and was suspended, thus causing a reduction in the number of potential patients for recruitment. Tests could not be performed on participants who did not attend the assessments in the exercise laboratory.[15] The outcomes collected by pen and paper were gathered by mail from these participants.

The study was prospectively registered at ClinicalTrials.gov (NCT03717727), and the study protocol has been described in detail elsewhere.[16] Guidelines were followed in reporting.[15 17–19]

Participants

At the preoperative polyclinic visit, eligibility screening was performed for individuals aged 60–75 with knee OA (n=78) who were scheduled to undergo TKR surgery and were interested in participating in the study. The inclusion criteria were (1) first primary unilateral TKR, (2) mechanical axis of the limb in varus, (3) posterior stabilising or cruciate-retaining prosthesis and (4) normal vision with or without eyeglasses. Individuals were excluded if they had fractures, rheumatoid arthritis or other biomechanical disruptions in the affected lower limb within 1 year before surgery, a diagnosed memory disorder, cognitive impairment or a neurological condition. Before the TKR surgery, the researcher contacted patients by phone, ensured eligibility, provided a detailed description of the study and scheduled the time for the baseline assessment (n=52) in the exercise laboratory. Eligible individuals provided written informed consent before enrolment.

Randomisation and blinding

Patients were randomly allocated to either the IG or CG. Randomisation was performed using blocks of two and four in random order and stratified by the place of recruitment, gender and 10 s time limit in the timed Up and Go (TUG) test (fast/slow).[20 21] Two persons unrelated to the study implemented the random allocation sequence and concealment: one generated a randomisation procedure, and the other concealed group allocation cards to consecutively marked opaque envelopes. Allocation to the groups occurred at the end of the baseline assessment. The research physical therapist assigned the participants to groups by selecting and opening a valid envelope. Participants allocated to the IG received gaming equipment, installation and exergaming instructions. The blinding of participants and outcome assessors was impossible because of the nature of the interventions and the collected exergame-related questionnaires.

Outcomes

Primary outcomes

Knee-related function and pain were assessed using the Oxford Knee Score (OKS) 12-item questionnaire.[22 23] Each item is scored from 0 to 4, from the highest to the lowest severity of function and pain. The total score ranged from 0 to 48, with 48 indicating the best function and the least (or no) pain.

Mobility was measured using the TUG test.[24] Time in seconds was measured while the participant raised from a chair, walked 3 m, turned, walked back to the chair and sat down. A shorter test time indicated better mobility.

Secondary outcomes

Knee pain was assessed using the pen-and-paper Visual Analogue Scale (VAS).[25] Participants rated their average pain intensity over a week from 0 to 100, ranging from no knee pain to the worst possible knee pain.

Walking was measured using the 10 m walking test.[26] The time in seconds was measured while the participant walked 10 m fast. The results were expressed as walking

Table 1 Baseline characteristics of the patients scheduled to undergo a TKR surgery

Variables	Intervention group (exergame) (n=25)	Control group (standard exercise) (n=27)
Age, years, mean (SD)	66.9 (3.1)	66.4 (4.5)
Women, n (%)	16 (64.0)	17 (63.0)
Healthcare district, n (%)		
South West Health Care District	17 (68.0)	20 (74.1)
Central Finland Health Care District	8 (32.0)	7 (25.9)
Height, mean (SD)	167.4 (9.3)	167.0 (7.9)
Weight, mean (SD)	86.9 (16.0)	84.4 (10.4)
BMI, mean (SD)	31.0 (5.3)	30.3 (3.4)
ICD-10, n (%)*		
M17.0	8 (32.0)	9 (33.3)
M17.1	17 (68.0)	18 (66.7)
Model of the completed TKR, n (%)		
Cruciate retaining	24 (96.0)	27 (100.0)
Posterior stabilising	1 (4.0)	0 (0.0)
Knee pain (VAS 0–100), mean (SD)	54.8 (20.4)	53.7 (20.9)
Self-reported comorbidity, n (%)		
OA in joints other than the knee	10 (40.0)	9 (33.3)
Musculoskeletal disease other than OA	2 (8.7)†	3 (11.1)
Tibia fracture in the operated lower limb	1 (4.0)	0 (0.0)
Diabetes	3 (12.0)	4 (14.8)
Coronary artery disease	1 (4.0)	2 (7.4)
Hypertension	11 (44.0)	17 (63.0)
Respiratory disease	1 (4.0)	2 (7.4)
Life situation, n (%)		
Working	4 (16.0)	8 (29.6)
Unemployed	0 (0.0)	1 (3.7)
Retired	21 (84.0)	18 (66.7)
Daily walking, km, n (%)		
<0.5	1 (4.0)	1 (3.7)
0.5–0.9	9 (36.0)	6 (22.2)
1–3.9	15 (60.0)	14 (51.9)
4–5.9	0 (0.0)	2 (7.4)
≥6	0 (0.0)	4 (14.8)
Level of physical activity (PA), n (%)		
Hardly any PA	3 (12.0)	0 (0.0)
Light PA, 1–2 times a week	5 (20.0)	8 (29.6)
Light PA, >2 times a week	6 (24.0)	5 (18.5)
Moderate PA, 1–2 times a week	4 (16.0)	5 (18.5)
Moderate PA, >2 times a week	7 (28.0)	6 (22.2)
Active sports, >2 times a week	0 (0.0)	3 (11.1)
Competitive sports	0 (0.0)	0 (0.0)

Continued

Table 1 Continued

*M17.0 Bilateral primary osteoarthritis of knee, M17.1 Unilateral primary osteoarthritis of knee.
†n=23.
BMI, body mass index; ICD-10, International Classification of Diseases 10th Revision; OA, osteoarthritis; VAS, Visual Analogue Scale.

speed (m/s). A higher m/s value in the test indicated better walking performance.

Lower extremity performance was measured using the short physical performance battery (SPPB) test.[27] The SPPB test includes three subtests measuring balance, mobility and lower extremity strength, each scored from 0 to 4, from poor to best performance. The total score ranged from 0 to 12, with 12 indicating the best lower extremity performance.

Muscle strength of the operated lower limb was measured using isometric knee extension and flexion force tests.[28] A higher force value in Newton metres indicated better lower-extremity muscle strength.

The knee range of movement (ROM) of the operated lower limb was measured using a goniometer.[29] A smaller degree of active knee extension and a higher degree of active knee flexion (ie, wider ROM) indicated a better joint range of motion.

Early satisfaction with the operated knee was assessed with the question: 'How satisfied are you with your operated knee?' Responses were scored from 1 to 4, from 'very satisfied' to 'very dissatisfied'.

Interventions

All participants received their usual treatment after TKR. In addition, regardless of the assigned group, all participants received standard protocol home exercise instructions from a physical therapist during the hospital stay. Interventions in the IG and CG were initiated after discharge and lasted for 16 weeks. In structured diaries, the participants reported the duration of daily exergaming, standard protocol exercising, and other physical activity (PA). Self-reported PA minutes were calculated as metabolic equivalents of task hours per week according to the marked activity and self-evaluated intensity.[30] In addition, gaming computers recorded the daily duration of the games. Participants' adverse events spontaneously mentioned were recorded, and their possible causal connections to the interventions were assessed.

Home exercise by standard protocol

The CG protocol included 11–12 exercises. Progression of postoperative exercise over time was ensured by increasing the exercise time (from 2 to 5 times a day), the number of repetitions (from 3 to 15), and the number of sets (from 1 to 3).

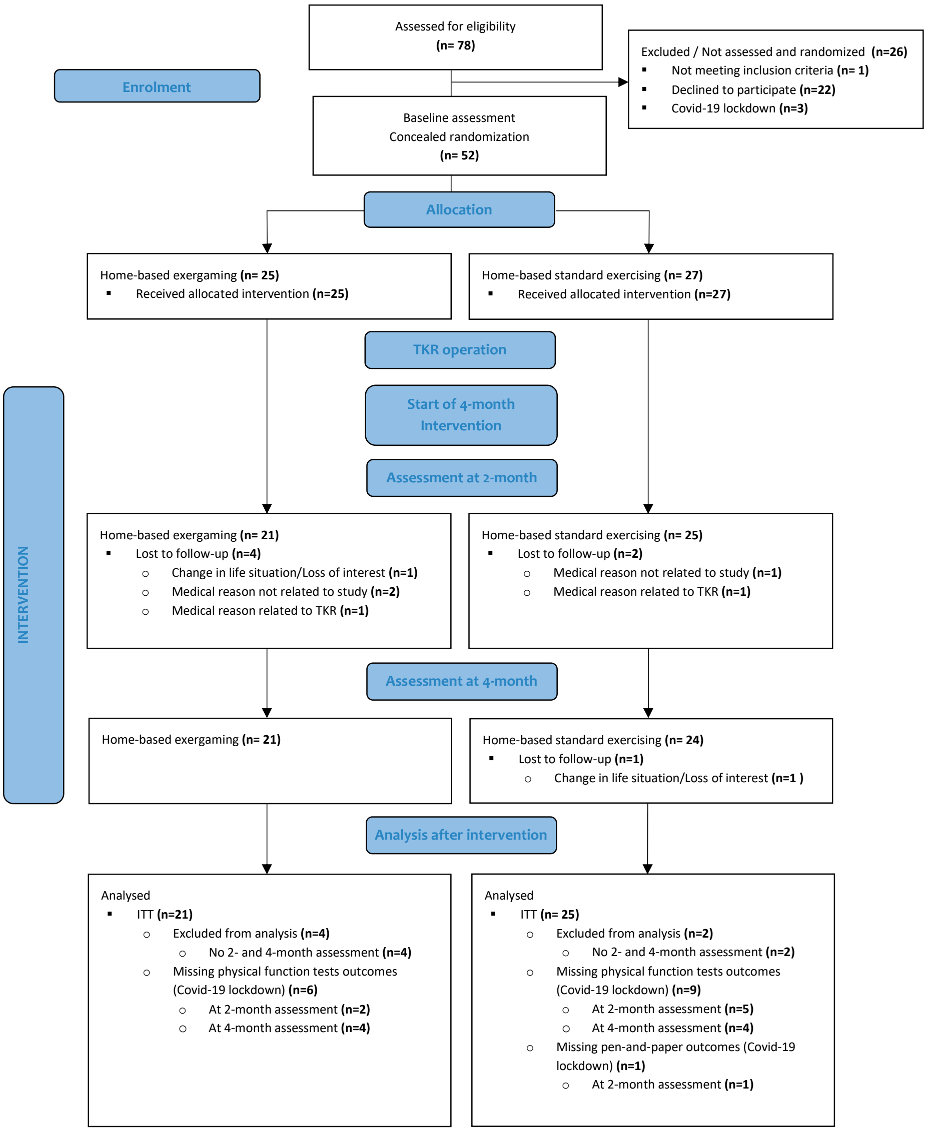

Figure 1 Flow diagram. ITT, intention to treat; TKR, total knee replacement.

Home-based exergame intervention

The IG protocol included 11 games. Progression of postoperative exergaming over time was ensured by changing the weekly number of games (from 4 to 5 exergames), duration (from 90 s to 360 s), number of repetitions (from 5 to 12), number of sets (from 1 to 3) and intensity (from slow to fast). Participants were instructed to complete the exergame programme assigned to the intervention week several times a day.

Interventions are presented in more detail in the protocol.[16]

Sample size

The calculation of sample size was based on the primary outcome OKS and was determined to be 100 participants to detect 5 point difference between groups at an alpha of 0.05, power of 80%, and anticipate a 10% drop-out rate during follow-up.[31 32]

Statistical methods

All available data in the full analysis set were analysed using Stata software (V.17.0; StataCorp). Participants assigned to the IG or CG received the allocated intervention. They had any assessments at the baseline, and

Table 2 Self-reported standard protocol exercising, exergaming and PA from baseline to 2 months and from 2 months to the end of the intervention in the control and intervention groups

	Control group (n=25)			Intervention group (n=21)					
	Standard exercise		PA	Exergaming		Standard exercise			PA
Weeks	Hours	Hours/week	MET hours	Hours	Hours/week	Hours	Hours/week	Total hours	MET hours
1–8	19.0 (16.9)	2.4 (2.1)	122.0 (164.7)	19.9 (23.6)	2.5 (3.0)	5.7 (6.1)	0.7 (0.8)	25.6 (23.6)	117.5 (95.6)
9–16	17.4 (21.0)	2.2 (2.6)	180.8 (146.1)	15.6 (17.1)	2.0 (2.1)	4.6 (4.7)	0.6 (0.6)	20.2 (18.8)	179.4 (85.0)

Values are mean (SD).
MET, metabolic equivalent of task; PA, physical activity.

2-month or 4-month follow-ups were included in the intention-to-treat (ITT) analysis. Missing data resulting from drop-outs, technical or human errors in the data collection and interruptions to routine data collection were not imputed. Repeated measurements were obtained at different time points, including baseline and 2 and 4 months. Repeated measures of the changes in primary and secondary outcomes were compared between the IG and CG using mixed-effects models and an unstructured covariance structure (ie, the Kenward-Roger method for calculating df). The fixed effects included group, time, and group×time interactions. Mixed models allow the analysis of unbalanced datasets without imputation.

RESULTS

Recruitment started in November 2018 and ended in December 2020 at the scheduled closure date. Fifty-two eligible and voluntary TKR patients were randomly allocated to the IG (n=25) or CG (n=27) after baseline assessment. Both groups' demographic and clinical characteristics were similar at the baseline (table 1). Figure 1 presents the flow and number of randomly assigned participants by the group throughout the study, together with losses after randomisation. The drop-out rate during the 4-month intervention period was 16.0% in the IG and 11.1% in the CG. Drop-outs related to TKR (n=2) were due to inflammation in the operated prosthesis. Forty-six participants (IG, n=21; CG, n=25) were included in the ITT analysis. No adverse events related to the intervention were observed.

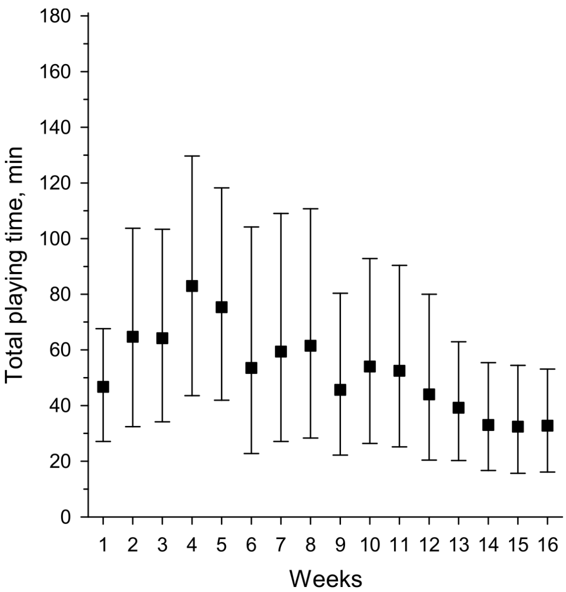

Figure 2 Mean minutes of exergaming from gaming computers during the 4-month intervention (n=21).

Adherence

There were no differences in the mean time spent for exergaming or standard protocol exercise in weeks 1–8 and 9–16, either in the IG or CG (figure 2, table 2). The IG had more PA during weeks 9–16 than during weeks 1–8 (table 2). Based on the gaming computers, two participants did not exergame. Several patients did not continue exergaming until the end of the study protocol (exergamed for less than 2 months (n=3), 3 months (n=2), or 4 months (n=3)).

Baseline assessments were performed on average 7.5 days (SD 3.7) before surgery, and follow-up assessments on average −0.2 days (SD 5.3) at 2 month, and 2.4 days (SD 7.2) at 4 months time point. Exceeding the target time limits was due to participants' schedules (n=15) or the COVID-19 lockdown (n=4).

Outcomes

The TUG improved more in the IG than the CG over the 2 months (p=0.019) and the 4 months (p=0.040) time. Overall, during the 4-month intervention, in the IG, the mean TUG improved by −1.9 s (95% CI −2.9 to −1.0), and in the CG, it changed by −0.6 s (95% CI −1.4 to 0.3). There were no statistical differences between the groups in the OKS, but the score changed over the 4-month intervention in the IG by 12.1 points (95% CI 9.1 to 15.1) and in the CG by 9.8 points (95% CI 7.1 to 12.6). There were no statistical differences between the groups either in the secondary outcomes. Table 3, figure 3 and online supplemental appendix present the primary and secondary outcome changes from baseline in the IG and CG.

After the intervention period in the IG (n=21), participants were either satisfied (52.4%) or very satisfied (47.6%) with their knees that had undergone an

Table 3 Results for primary and secondary outcomes for the control and intervention groups

	Baseline		Change from baseline to 4 months		
	Control group (n=25)	Intervention group (n=21)	Control group (n=25)	Intervention group (n=21)	
	Mean (SD)	Mean (SD)	Mean (95% CI)	Mean (95% CI)	P value
OKS	26.9 (6.5)	26.7 (6.7)	9.8 (7.1 to 12.6)	12.1 (9.1 to 15.1)	0.27
TUG	8.3 (1.7)	9.4 (3.6)	−0.6 (−1.4 to 0.3)	−1.9 (−2.9 to −1.0)	0.04
Pain	54.2 (21.6)	57.1 (18.3)	−26.7 (−36.4 to −17.0)	−36.3 (−46.7 to −25.8)	0.18
10-MWT	1.6 (0.3)	1.6 (0.4)	0.1 (−0.0 to 0.2)	0.2 (0.1 to 0.3)	0.06
SPPB					
Total	9.6 (1.5)	9.5 (1.5)	0.8 (0.1 to 1.4)	1.1 (0.4 to 1.7)	0.51
Balance	3.8 (0.5)	3.8 (0.5)	0.1 (−0.1 to 0.4)	−0.2 (−0.4 to 0.1)	0.11
Mobility	3.9 (0.3)	3.8 (0.8)	0.1 (−0.1 to 0.3)	0.2 (−0.0 to 0.4)	0.64
LE strength	2.0 (1.1)	2.0 (1.0)	0.5 (0.1 to 1.0)	1.1 (0.6 to 1.6)	0.12
Muscle force					
Extension	1.1 (0.4)	1.2 (0.5)	−0.1 (−0.2 to 0.0)	−0.1 (−0.2 to 0.0)	0.85
Flexion	0.6 (0.2)	0.6 (0.3)	0.1 (−0.0 to 0.1)	0.1 (−0.0 to 0.3)	0.88
ROM					
Extension	6.6 (4.1)	7.3 (7.7)	0.1 (−2.7 to 2.9)	−0.5 (−3.5 to 2.5)	0.76
Flexion	107.0 (13.0)	107.0 (18.0)	−7.0 (−13.0 to -2.0)	−1.0 (−8.0 to 5.0)	0.17

Group mean and SD values at baseline, mean and 95% CI values indicating the within-group change from baseline to the end of the 4-month intervention period, and p values indicating the intergroup change in 4-month intervention.
LE, lower extremity; Muscle force, isometric muscle force of the operated lower limb (Nm/weight); 10-MWT, 10 m Walking Test; OKS, Oxford Knee Score ; ROM, range of motion; SPPB, Short Physical Performance Battery; TUG, Timed Up and Go.

operation. In the CG (n=25), participants were very unsatisfied (8.7%), unsatisfied (17.4%), satisfied (39.1%), or very satisfied (34.8%) with their operations.

DISCUSSION

Older adults who underwent TKR surgery participated in the 4-month home-based intervention using customised exergames, which improved their mobility more than those who exercised by the standard home exercise protocol. In addition, early satisfaction seemed to be more frequent in the IG. In both groups, there were positive changes in knee-related pain and physical function, including knee-related function, walking and lower extremity performance and strength over the 4 months; however, there were no statistically significant differences between the groups. This study's results align with earlier studies investigating the use of exergames in enhancing physical function and pain in post-TKR rehabilitation.[33 34]

When observing changes in mobility using the TUG, improvement was greater in the IG than in the CG, both in the middle and at the end of the intervention. For example, a similar difference between guided high-intensity and low-intensity training after TKR has not been observed.[35] The difference between IG and CG may be due, for example, to how the exergames may steer the training in a more progressive and goal-oriented direction than the instructions given for standard exercise. Moreover, it should be noted that the TUG did not change in the CG in the 2-month and 4-month follow-up points.

There were no intergroup changes when assessing changes in knee-related function and pain using the OKS. Positive changes were observed in both groups, indicating normal healing after TKR. When evaluating 95% CI, it can be speculated that when increasing the number of participants, CIs would narrow; thus, there

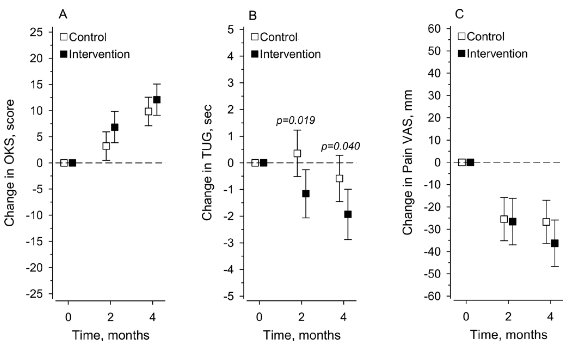

Figure 3 Mean changes in the Oxford Knee Score (A), Timed Up and Go (B) and knee pain intensity (C) for control (n=25) and intervention (n=21) groups from the baseline to the mid-intervention at 2 months and the end of intervention at 4 months.

may be significant differences in change between the groups.

When evaluating the clinical relevance of changes in knee-related function and pain using the OKS, the mean change in both groups was more than the estimate of the minimal clinically important change (MCIC) in the OKS in patients with TKR.[31] In addition, a change in the OKS of 11 points or more 6 months after TKR has been related to satisfaction with the surgery.[36] In the IG, this limit was already exceeded at 4 months, and 100% of the participants were either satisfied or very satisfied with the operated knee. In the CG, the percentage was 74%. The TUG MCIC has not been validated in patients with TKR. However, at 4 months, the mean change in the IG was similar to the TUG MCIC in lumbar surgery patients[37] and thus may also support the observed early satisfaction. Moreover, gamification may affect patients' expectations and experience of TKR and, thus, overall satisfaction.[38]

At 4 months, there were no significant intergroup changes in physical function or pain in the secondary outcomes. However, the pain intensity and lower extremity performance in both groups and walking in the IG changed slightly positively. When observing the results of the muscle force tests and knee ROM measures, there were no within-group changes in knee extension or knee flexion muscle force or knee extension ROM. The only negative change was observed in the knee flexion ROM in the CG, while in the IG, there was neither a negative nor positive change. Bade *et al*,[39] who assessed patients with TKR following a standard rehabilitation programme, observed similar within-group results at 3 and 6 months after surgery; the knee flexion ROM remained below the baseline level.

The participants' self-reported adherence to home exercise during the intervention was similar between the groups. However, the volume of exergaming and standard exercise varied widely between the participants over the intervention period. This may reflect the positive changes in physical function and pain achieved within 2 months, which may lower interest or motivation for rehabilitation. Moreover, variation may reflect interest or loss of training through novel games or individuals' choices to exercise in the preferred way.[6] In addition, this may be due to an increase in other self-reported PA,[40] observed in the IG and is a positive change compared with the finding that PA may remain low during the first months after TKR surgery.[41 42]

The strength of this study is the accurate design and implementation of a dual-centre RCT.[16] The randomisation was successful, and outcome variables selected in collaboration with researchers, orthopaedists and physiotherapists were validated and commonly used to measure the physical function and pain of patients with TKR.[22 26 43–47] Self-employed therapeutic exercise implemented at participants' homes ensured that despite the limitations caused by the COVID-19 pandemic in 2020, participants could continue therapeutic exercise in the assigned group without compromising their rehabilitation.

Study limitations

This study has several limitations. First, the number of participants was low, and half of the planned sample size was achieved in 2020 due to COVID-19. Second, assessors were not blinded after the baseline assessment because of the nature of the interventions and game-specific questionnaires collected from the exergame group. This may pose a risk of bias to the physical function follow-up assessments performed by a research physical therapist. Finally, due to COVID-19, some of the outcomes gathered by physical tests were not measured in this study. Because of the small sample size, the study results of physical function are indicative and will limit the generalisation and interpretation of the results. Future studies should aim to conduct similar studies among a larger cohort of participants.

CONCLUSIONS

In patients with TKR, training at home with customised exergames was more effective in mobility and early satisfaction and as effective as standard exercise compared with pain and other physical functions. In both groups, knee-related function and pain improvement can be considered clinically meaningful. Although exergaming was not superior to the standard protocol, it could be used in unsupervised home-based rehabilitation of physical function and pain after TKR.

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Acknowledgements The authors thank the funders, professionals in the Turku University Hospital, and Central Finland Central Hospital who were involved in the recruitment, and patients with TKR who participated in the study.

Contributors All authors substantially contributed to the conception and design of the work. MJ, NK, JP, KP, HK, MK, KM and EA participated in the recruitment of participants. MJ, NK and EA collected the data. MJ, HK, AH and EA analysed and interpreted the data. MJ drafted the manuscript. All authors commented on the drafted manuscript and critically revised it. All authors approved the final version of the manuscript. AH is responsible for the overall content as guarantor.

Funding This research was supported by the Päivikki and Sakari Sohlberg Foundation (personal grant to M. Janhunen), the Business Finland (grant numbers: 5794/31/2016, 5941/31/2016, 6057/31/2016) and Finnish partner companies: SE Innovations Oy (Senior Some Oy), Suunto Oy, Physiotools Oy, GoodLife Technology Oy, Lingsoft Oy, eSeteli Palveluverkko Oy, PN Turku Oy, Ade Animations Design & Effects Oy, Adesante Oy, 4FeetUnder, Intechso and Realmax Oy.

Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Consent obtained directly from patient(s).

Ethics approval This study involves human participants and was approved by Ethics Committee of the South West Finland Health Care District (register ETMK Dnro 66/1801/2018, 19 June 2018). Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement All data relevant to the study are included in the article or uploaded as online supplemental information. Metadata has been published in the Jyväskylä University Digital Repository (http://dx.doi.org/10.17011/jyx/dataset/85350).

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REFERENCES

1 Dávila Castrodad IM, Recai TM, Abraham MM, *et al*. Rehabilitation protocols following total knee arthroplasty: a review of study designs and outcome measures. *Ann Transl Med* 2019;7(Suppl 7):S255.
2 Mistry JB, Elmallah RDK, Bhave A, *et al*. Rehabilitative guidelines after total knee arthroplasty: a review. *J Knee Surg* 2016;29:201–17.
3 Buhagiar MA, Naylor JM, Harris IA, *et al*. Assessment of outcomes of inpatient or clinic-based vs home-based rehabilitation after total knee arthroplasty: a systematic review and meta-analysis. *JAMA Netw Open* 2019;2:e192810.
4 Taylor LM, Kerse N, Frakking T, *et al*. Active video games for improving physical performance measures in older people: a meta-analysis. *J Geriatr Phys Ther* 2018;41:108–23.
5 Pirovano M, Surer E, Mainetti R, *et al*. Exergaming and rehabilitation: a methodology for the design of effective and safe therapeutic exergames. *Entertainment Computing* 2016;14:55–65.
6 Skjæret N, Nawaz A, Morat T, *et al*. Exercise and rehabilitation delivered through exergames in older adults: an integrative review of technologies, safety and efficacy. *Int J Med Inform* 2016;85:1–16.
7 Howes SC, Charles DK, Marley J, *et al*. Gaming for health: systematic review and meta-analysis of the physical and cognitive effects of active computer gaming in older adults. *Phys Ther* 2017;97:1122–37.
8 Gonçalves A, Muñoz J, Cameirão MS, *et al*. The benefits of custom exergames for fitness, balance, and health-related quality of life: a randomized controlled trial with community-dwelling older adults. *Games Health J* 2021;10:245–53.
9 Corregidor-Sánchez AI, Segura-Fragoso A, Rodríguez-Hernández M, *et al*. Effectiveness of virtual reality technology on functional mobility of older adults: systematic review and meta-analysis. *Age Ageing* 2021;50:370–9.
10 Gianola S, Stucovitz E, Castellini G, *et al*. Effects of early virtual reality-based rehabilitation in patients with total knee arthroplasty: a randomized controlled trial. *Medicine (Baltimore)* 2020;99:e19136.
11 Yoon S, Son H. EFFECTS of full immersion virtual reality training on balance and knee function in total knee replacement patients: A randomized controlled study. *J Mech Med Biol* 2020;20:2040007.
12 Fung V, Ho A, Shaffer J, *et al*. Use of nintendo wii fit. *Physiotherapy* 2012;98:183–8.
13 Blasco J, Igual-Camacho C, Blasco M, *et al*. The efficacy of virtual reality tools for total knee replacement rehabilitation: A systematic review. *Physiother Theory Pract* 2021;37:682–92.
14 Janhunen M, Karner V, Katajapuu N, *et al*. Effectiveness of exergame intervention on walking in older adults: A systematic review and meta-analysis of randomized controlled trials. *Phys Ther* 2021;101.
15 Orkin AM, Gill PJ, Ghersi D, *et al*. Guidelines for reporting trial protocols and completed trials modified due to the COVID-19 pandemic and other extenuating circumstances: the CONSERVE 2021 statement. *JAMA* 2021;326:257.
16 Aartolahti E, Janhunen M, Katajapuu N, *et al*. Effectiveness of gamification in knee replacement rehabilitation: protocol for a randomized controlled trial with a qualitative approach. *JMIR Res Protoc* 2022;11:e38434.
17 Hoffmann TC, Glasziou PP, Boutron I, *et al*. Better reporting of interventions: template for intervention description and replication (tidier) checklist and guide. *BMJ* 2014;348:g1687.
18 Hopewell S, Clarke M, Moher D, *et al*. CONSORT for reporting randomized controlled trials in journal and conference abstracts: explanation and elaboration. *PLoS Med* 2008;5.
19 Moher D, Hopewell S, Schulz KF, *et al*. Consort 2010 explanation and elaboration: updated guidelines for reporting parallel group randomised trials. *BMJ* 2010;340:c869.
20 Bade MJ, Wolfe P, Zeni JA, *et al*. Predicting poor physical performance after total knee arthroplasty. *J Orthop Res* 2012;30:1805–10.
21 Mizner RL, Petterson SC, Clements KE, *et al*. Measuring functional improvement after total knee arthroplasty requires both Performance-based and patient-report assessments: a longitudinal analysis of outcomes. *J Arthroplasty* 2011;26:728–37.
22 Dawson J, Fitzpatrick R, Murray D, *et al*. Questionnaire on the perceptions of patients about total knee replacement. *J Bone Joint Surg Br* 1998;80:63–9.
23 Reito A, Järvistö A, Jämsen E, *et al*. Translation and validation of the 12-Item Oxford knee score for use in Finland. *BMC Musculoskelet Disord* 2017;18:74.
24 Podsiadlo D, Richardson S. The timed " up & go ": a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc* 1991;39:142–8.
25 Thong ISK, Jensen MP, Miró J, *et al*. The validity of pain intensity measures: what do the NRS, vas, VRS, and FPS-R measure? *Scand J Pain* 2018;18:99–107.
26 Unver B, Baris RH, Yuksel E, *et al*. Reliability of 4-meter and 10-meter walk tests after lower extremity surgery. *Disabil Rehabil* 2017;39:2572–6.
27 Guralnik JM, Simonsick EM, Ferrucci L, *et al*. A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. *J Gerontol* 1994;49:M85–94.
28 Maffiuletti NA, Bizzini M, Desbrosses K, *et al*. Reliability of knee extension and flexion measurements using the con-trex isokinetic dynamometer. *Clin Physiol Funct Imaging* 2007;27:346–53.
29 Gogia PP, Braatz JH, Rose SJ, *et al*. Reliability and validity of goniometric measurements at the knee. *Phys Ther* 1987;67:192–5.
30 Ainsworth BE, Haskell WL, Herrmann SD, *et al*. 2011 compendium of physical activities: a second update of codes and Met values. *Med Sci Sports Exerc* 2011;43:1575–81.
31 Beard DJ, Harris K, Dawson J, *et al*. Meaningful changes for the oxford hip and knee scores after joint replacement surgery. *J Clin Epidemiol* 2015;68:73–9.
32 Judge A, Arden NK, Cooper C, *et al*. Predictors of outcomes of total knee replacement surgery. *Rheumatology (Oxford)* 2012;51:1804–13.
33 Gazendam A, Zhu M, Chang Y, *et al*. Virtual reality rehabilitation following total knee arthroplasty: a systematic review and meta-analysis of randomized controlled trials. *Knee Surg Sports Traumatol Arthrosc* 2022;30:2548–55.
34 Peng L, Zeng Y, Wu Y, *et al*. Virtual reality-based rehabilitation in patients following total knee arthroplasty: a systematic review and meta-analysis of randomized controlled trials. *Chin Med J (Engl)* 2021;135:153–63.
35 Bade MJ, Struessel T, Dayton M, *et al*. Early high-intensity versus low-intensity rehabilitation after total knee arthroplasty: a randomized controlled trial. *Arthritis Care Res (Hoboken)* 2017;69:1360–8.
36 Judge A, Arden NK, Kiran A, *et al*. Interpretation of patient-reported outcomes for hip and knee replacement surgery: identification of thresholds associated with satisfaction with surgery. *J Bone Joint Surg Br* 2012;94:412–8.

37 Maldaner N, Sosnova M, Ziga M, *et al*. External validation of the minimum clinically important difference in the timed-up-and-go (TUG) test after surgery for lumbar degenerative disc disease. *Spine* 2021.
38 Hamilton DF, Lane JV, Gaston P, *et al*. What determines patient satisfaction with surgery? A prospective cohort study of 4709 patients following total joint replacement. *BMJ Open* 2013;3:e002525.
39 Bade MJ, Kohrt WM, Stevens-Lapsley JE. Outcomes before and after total knee arthroplasty compared to healthy adults. *J Orthop Sports Phys Ther* 2010;40:559–67.
40 Matsunaga-Myoji Y, Fujita K, Ide S, *et al*. Changes in actual daily physical activity and patient-reported outcomes up to 2 years after total knee arthroplasty with arthritis. *Geriatr Nur (Lond)* 2020;41:949–55.
41 Mills K, Falchi B, Duckett C, *et al*. Minimal change in physical activity after lower limb joint arthroplasty, but the outcome measure may be contributing to the problem: a systematic review and meta-analysis. *Physiotherapy* 2019;105:35–45.
42 Sašek M, Kozinc Ž, Löfler S, *et al*. Objectively measured physical activity, sedentary behavior and functional performance before and after lower limb joint arthroplasty: a systematic review with meta-analysis. *J Clin Med* 2021;10:5885:24.:.
43 Poitras S, Wood KS, Savard J, *et al*. Assessing functional recovery shortly after knee or hip arthroplasty: a comparison of the Clinimetric properties of four tools. *BMC Musculoskelet Disord* 2016;17:478.
44 Lienhard K, Lauermann SP, Schneider D, *et al*. Validity and reliability of isometric, isokinetic and isoinertial modalities for the assessment of quadriceps muscle strength in patients with total knee arthroplasty. *J Electromyogr Kinesiol* 2013;23:1283–8.
45 Wylde V, Bruce J, Beswick A, *et al*. Assessment of chronic postsurgical pain after knee replacement: a systematic review. *Arthritis Care Res (Hoboken)* 2013;65:1795–803.
46 Medina-Mirapeix F, Vivo-Fernández I, López-Cañizares J, *et al*. Five times sit-to-stand test in subjects with total knee replacement: reliability and relationship with functional mobility tests. *Gait Posture* 2018;59:258–60.
47 Brosseau L, Balmer S, Tousignant M, *et al*. Intra- and intertester reliability and criterion validity of the parallelogram and universal goniometers for measuring maximum active knee flexion and extension of patients with knee restrictions. *Arch Phys Med Rehabil* 2001;82:396–402.

Supplementary information

Table. Mean (SD) values of Oxford Knee Score (OKS) questionnaire, Timed Up and Go (TUG) test and knee pain intensity in the control and intervention groups at baseline, 2 months and 4 months.

	Control N=25 Mean (SD)	Intervention N=21 Mean (SD)
OKS		
Baseline	26.9 (6.5)	26.7 (6.7)
2 months	30.3 (5.5)	33.4 (6.3)
4 months	36.7 (6.7)	38.6 (6.1)
TUG		
Baseline	8.3 (1.7)	9.4 (3.6)
2 months	8.7 (1.6)	8.2 (1.5)
4 months	7.7 (1.2)	7.6 (1.5)
Pain (VAS)		
Baseline	54.2 (21.6)	57.1 (18.3)
2 months	28.7 (20.0)	30.5 (21.0)
4 months	27.0 (27.5)	20.8 (20.3)