The Next Step

Perturbation-based balance training and falls prevention in older adults

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Perturbation-based balance training and falls prevention in older adults

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General Introduction

Ageing population

With improving health, people are living longer; both the number and proportion of older people in the population is increasing.[1] While in 1990 the global percentage of people aged 65 years and older was 6%, this has increased to 9% in 2019, and is expected to further increase to 16% in 2050. In absolute numbers, there were 703 million people worldwide aged 65 years or older in 2019, which is projected to double to 1.5 billion in 2050.[2] Population ageing presents opportunities, but also challenges, for example in the area of health and healthcare.[3] As ageing is associated with a decline in physiological, physical, mental and cognitive abilities, an ageing population has an increasing number of people needing health and related care.[4,5]

Falls in older adults

Among older adults, falls are one of the most common health concerns. A fall is defined as ''an unexpected event in which the person comes to rest on the ground, floor, or lower level''.[6] Annually, approximately one in three adults aged 65 years and older, and 50% of adults above the age of 80 years, experience a fall.[7] In 2020, every five minutes an older adult in the Netherlands visited the emergency department due to a fall.[8] Falls can have many adverse consequences, both on the individual as well as societal level, and are associated with functional decline, loss of autonomy, and reduced quality of life.[9] In 2020, falls in the Netherlands caused severe injuries in 76,800 older adults (2300 per 100,000 residents), led to 36,700 hospital admissions (1100 per 100,000 residents), 13,300 temporary or permanent admissions to a nursing home (390 per 100,000 residents), and caused 5,012 deaths. The direct medical costs resulting from falls in the Netherlands amounted to 1.1 billion euros.[8]

Falls are a complex and multifactorial problem, with numerous factors that can increase the risk of falling. These factors can be related to increased individual susceptibility such as impaired balance control or reduced muscle strength (i.e., intrinsic risk factors) or environmental hazards such as loose rugs or poor lighting (i.e., extrinsic risk factors).[10] After the first fall incident, the risk of sustaining future falls is greatly increased (odds ratio (OR) 2.8 for all fallers, and 3.5 for recurrent fallers).[11,12] Many fallers will also develop a fear of falling (OR 5.72 compared to older non-fallers), which can in turn lead to activity avoidance (OR 4.64 compared to older non-fallers).[13] As both fear of falling and activity avoidance are also risk factors for falls[14], this illustrates one of the ways that a fall can lead older adults to end up in a negative cycle **(Figure 1.1)**.

Figure 1.1 Example of how a fall incident can lead to a negative cycle, increasing the risk of sustaining recurrent falls.

The large number of fall risk factors have inspired the development of many strategies to decrease falls in older adults, each designed to address one or more of these risk factors. For example, exercise interventions aimed at improving muscle strength or balance control, or specific interventions aimed at decreasing fear of falling. If the risk of falls were to remain the same, with the ageing of the population it is expected that the number of falls in older adults will keep increasing and even double by 2060. Direct medical costs of falls are expected to increase even faster, and more than double to 2.4 billion euros within the next 10 years.[8] Therefore, the development and optimization of falls preventive interventions is essential.

Falls and balance

While falls are a complex and multifactorial problem, the ability to maintain and restore balance is a critical factor. Essentially, balance control is the need to keep the body's center of mass (CoM) within the limits of the base of support (BoS), or on track to a moving BoS.[15] Balance training is a form of exercise intervention that has been found to be particularly effective in reducing fall risk in older adults. A Cochrane review showed that gait and balance training could achieve overall reductions of 24% for the number of falls, and 13% for the number of fallers.[16]

However, it should be considered that balance is a multidimensional concept rather than an isolated quality. As the ability to balance is required for most physical activities, all dimensions of balance are required to achieve functional balance.[17]

Balance can be divided into three dimensions[17,18]:
1. Maintaining a posture, such as standing or sitting
2. Adjusting to voluntary movements
3. Reacting to external disturbances, such as slips or trips

Strategies to achieve, maintain or restore balance can be proactive (when the movement is anticipated), or reactive (when the movement is unexpected or needs to be adjusted).[19] In most balance training interventions to date, exercises are mostly focused on training proactive or predictive balance control, and less on reactive balance control. However, many falls in older adults (approximately 59% in community-dwelling older adults) are the result of unexpected perturbations during walking, such as slips or trips.[20] When a perturbation causes the body to lose stability, the last line of defense to prevent a fall is reactive balance.[21] Since recovery responses seem highly task-specific, and due to the additional speed and stability requirements of these reactions, it is unlikely that general balance training will also improve reactive balance control.[22] In recent years, there has been an increasing interest in interventions that are more task-specific to the recovery reactions required to prevent a fall.[23,24]

Perturbation-based balance training

Perturbation-based balance training (PBT), is a task-specific intervention that aims to improve reactive balance control after destabilizing perturbations in a safe and controlled environment.[25] During PBT, participants are exposed to unexpected balance perturbations during various activities of daily living, such as standing, walking, or rising from a chair.[26,27] Perturbations can be applied using various methods, each of them with their own specific advantages and challenges. For example, methods can range from therapist applied pushes or pulls[28] to (instrumented) treadmill systems[29], walkways with low-friction plates[27], or moveable platforms.[30]

In reaction to an unexpected perturbation, older adults show less effective recovery responses than younger adults.[31] Physiological changes in the ageing process lead to decreased reactive balance control, including decreased magnitude of postural responses, delayed onset of muscle responses, and an increased level of co-activation in muscles.[32-34] There may be a substantial decline in reactive balance control even in community-dwelling older adults who walk independently, which will only become evident when a slip or a trip occurs.[35] Despite this decline, the capacity to adapt and improve reactive balance control with training does not appear to be affected by age.[36,37] Thus, training of reactive balance control such as PBT may be an effective strategy to improve balance recovery reactions in older adults, and consequently reduce fall risk in daily life.

There is a growing body of evidence for the effectiveness of PBT. Many studies have focused on direct balance adaptations from PBT, within a single session of 12-28 unannounced perturbations over a number of walking trials. These studies demonstrated significant improvements in various balance recovery parameters (such as center of mass position and velocity)[27,38-42], and reduced laboratory-induced falls.[27,41,43] Studies including a follow-up measurement found retention of improvements in balance recovery parameters at 6 months, and of reductions in laboratory-induced falls over a period of 12 months.[27,38] Other outcomes have been less extensively studied, but some studies have reported significant beneficial effects of PBT on reaction time[26,43,44] and single leg stance time (44), and one pilot study found a trend towards improved Berg Balance Scale (BBS), and Timed Up and Go (TUG) test scores[29] in older adults. The effects of PBT on falls in daily life of older adults have been the topic of more studies, which were combined in two meta-analyses showing promising results. Mansfield *et al.*, reported a significant reduction (46%) in falls rates in older adults with and without Parkinson's disease (overall rate ratio 0.54, 95% confidence interval (CI) 0.34 to 0.85, p=0.007).[45] The second meta-analysis, by Okubo *et al.*, reported a 52% reduction in rate of falls in community-dwelling older adults (relative attributable risk 0.52, 95% CI 0.35 to 0.76, p<0.0001).[46] PBT may have an additional advantage over more classical balance training interventions, in its potential to be effective even after very brief periods of training.[47-51] For example, Pai *et al*. reported a 50% reduction in daily-life falls in older adults over the course of a year after a single session of 24 walking perturbations.[50]

Despite the growing interest in PBT in research, there has been little transfer of PBT to clinical practice. Given the substantial burden of falls on individuals and society, it is essential to evaluate if promising new interventions such as PBT may be feasible and effective for application in clinical practice.

- personal motivation –

In my work as a physical therapist, as well as in my personal life, I have often witnessed the impact that a single fall incident can have on a person's life and their loved ones. Especially at older age, a fall can be a major life event. Besides direct physical consequences, falls can also have a psychological impact, leading to decreased balance confidence and a fear of falling again. Most importantly, the consequences of falls can negatively affect someone's daily life by decreasing the ability to live independently, participate in social activities or practice a beloved hobby. The wish to prevent as many people as possible from experiencing these consequences has inspired me to learn more about falls prevention. I learned that already much research was done in the field of falls prevention, and that many interventions have been developed. However, there is still room for improvement, especially considering that our population will continue to age which leads to an increased number of people in need of falls prevention. During my master's internship I first came into contact with a relatively new type of balance training that is aimed at improving the recovery response to unexpected balance disturbances, such as slips or trips. The task-specific nature of this intervention and the promising results of the first available studies sparked my interest and made me want to learn more about this type of balance training.

Aims and outline of this thesis

Falls present a substantial threat to the health and wellbeing of older adults. The ageing of the population presents an increasing need for effective and efficient falls prevention interventions. Perturbation-based balance training may be a promising intervention to improve balance control and prevent falls in the daily life of older adults. The aim of this thesis is to further our understanding of the effectiveness and applicability of this relatively new intervention in clinical practice, with the perspective that this knowledge could further the readiness of PBT for implementation in clinical practice.

The studies in this thesis were conducted in the setting of the Maastricht University Medical Center (MUMC+), and made use of the Computer Assisted Rehabilitation Environment (CAREN, Motek Medical BV). The CAREN is a dual-belt treadmill system embedded in a motion platform with 6 degrees of freedom that is surrounded by a 180 degree screen. The treadmill and the motion platform can both provide reactive balance challenges separately or combined, providing a wide array of possible types and directions of perturbation. Virtual reality environments, such as the forest road in ***Figure 1.2****, are projected onto the screen to make training activities more immersive. For measurements, the system's treadmill is force plate-instrumented and combined with a 12 camera Vicon Nexus motion capture system (Vicon Motion Systems, Oxford, UK). Participants wear a safety harness at all times when using the system, making it possible to challenge balance while being protected from injuries in case of an unsuccessful balance recovery.*

The Computer Assisted Rehabilitation Environment

Figure 1.2 *Picture of a participant during perturbation-based balance training on the Computer Assisted Rehabilitation Environment. Picture published with the participant's permission.*

To achieve our aim, we first started with an exploration of the topic. In **Chapter 2**, a systematic review is conducted to gain an overview of the current evidence for PBT for falls reduction in daily life of older adults. The characteristics of PBT in these studies are examined to present and discuss a number of considerations that may affect feasibility and effectiveness when applying PBT in clinical settings. **Chapter 3** aims to explore the extent to which stability following a novel perturbation and adaptability to repeated perturbations relate to falls history in older adults. This cross-sectional study compares data from community-dwelling older adults with and without a history of falls that completed a series of unperturbed and perturbed walking trials.

In **Chapter 4**, the lessons learned from the systematic review in chapter 2 are applied to the setting of the MUMC+ in the design of a PBT protocol. This study protocol describes how community-dwelling older adults who presented at the MUMC+ outpatient clinic after a fall incident will be included and randomized to study the short- (balance control and fear of falling) and long-term (falls and injurious falls in daily life) effects of PBT versus the current usual care. Embedded in this randomized controlled trial (RCT) is a qualitative study that will evaluate the acceptability of the PBT protocol.
The next two chapters of this thesis are about the clinical application, acceptability and results of the PBT protocol described in Chapter 4. In **Chapter 5**, a qualitative study design is applied with the aim of evaluating the acceptability of PBT in community-

dwelling older adults with a recent history of falls. Semi-structured interviews based on the Theoretical Framework of Acceptability[52] were conducted in a representative sample of participants who completed the PBT training protocol. **Chapter 6** reports the short-term effects of PBT on balance control and fear of falling in community-dwelling older adults. In a single-blind randomized controlled trial, older adults receive usual care (referral to a physiotherapist) with or without the addition of PBT.

Finally, **Chapter 7** of this thesis presents a general discussion of the methodologies of our studies, the findings in this thesis, and considers their implications for clinical practice. In addition, it discusses aims and directions for future research.

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2

Perturbation-based balance training for falls reduction among older adults: current evidence and implications for clinical practice

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Abstract

Falls are a leading cause of injury, hospitalization and even death among older adults. Although various strength and balance exercise interventions have shown moderate reductions in falls incidence among healthy older adults, no significant falls incidence improvements have been consistently seen in frail older adults or in patient groups with an increased falls risk (e.g. people with Parkinson's disease and stroke). This might be due to a lack of task specificity of previous exercise interventions to the recovery actions required to prevent a fall. Perturbation-based balance training (PBT) is an emerging task-specific intervention that aims to improve reactive balance control after destabilizing perturbations in a safe and controlled environment. Although early studies were carried out predominantly in research laboratory settings, work in clinical settings with various patient groups has been proliferating. A systematic search of recent PBT studies showed a significant reduction of falls incidence among healthy older adults and certain patient groups (e.g. people with Parkinson's disease and stroke), with clinically relevant reductions in frail older adults. The most practical methods in clinical settings might be treadmill-based systems and therapist-applied perturbations, and PBT that incorporates multiple perturbation types and directions might be of most benefit. Although more controlled studies with long-term follow-up periods are required to better elucidate the effects of PBT on falls incidence, PBT appears to be a feasible and effective approach to falls reduction among older adults in clinical settings.

Introduction

Falls and fall-related injuries represent a global public health concern for our aging societies. Approximately 30% of people aged >60 years experience a fall in a given year,[1,2] with older age and frailty independently increasing falls risk.[2-4] Older adults with neurological disorders, such as stroke and Parkinson's disease, are at an even higher risk of falling.[5] Falls are a leading cause of injury, hospitalization and even death among older adults;[1,6] therefore, evidence-based interventions for reducing falls and fall-related injuries in older populations are of great importance.

Moderate reductions in falls risk (approximately 15–20%) have been seen in healthy older adults after exercise interventions including combinations of strength, balance and aerobic exercises.[7,8] However, there is mixed evidence for whether such exercise interventions result in a significant reduction in falls incidence in frail, older adults.[9-11] Importantly, there is limited evidence for falls risk reduction after such strength and balance exercise interventions alone in older adults with Parkinson's disease[12,13] or after a stroke.[14] One potential reason for the inconsistency or lack of effectiveness of such general exercise interventions for falls reduction is the lack of task specificity to the recovery actions required to prevent a fall.[15,16] In order to recover balance after a postural disturbance, change-in-support movements (e.g. by taking compensatory steps or by grasping nearby objects for support) and counter rotations of body segments can be executed.[17,18] Training that targets such balance recovery mechanisms might be more effective than general exercise.[15,16,19,20]

The importance of task-specific training has led to increasing interest in a new approach called perturbation-based balance training (PBT).[21,22] PBT is a task-specific intervention that aims to improve reactive balance control (i.e. rapid reactions to instability) after destabilizing perturbations in a safe and controlled environment. Participants are exposed to unexpected balance perturbations (e.g. treadmill accelerations, waist pulls, cable-based trips, nudge from a therapist etc.; see **Figure 2.1** for examples) during tasks of daily living, such as standing, walking or rising from a chair.[19,23] The perturbations during PBT are unannounced in order to mimic the accidental and unexpected nature of falls in daily life,[21] and ensure that the task-specific approach of PBT is in concordance with the “specificity of learning” hypothesis.[24]

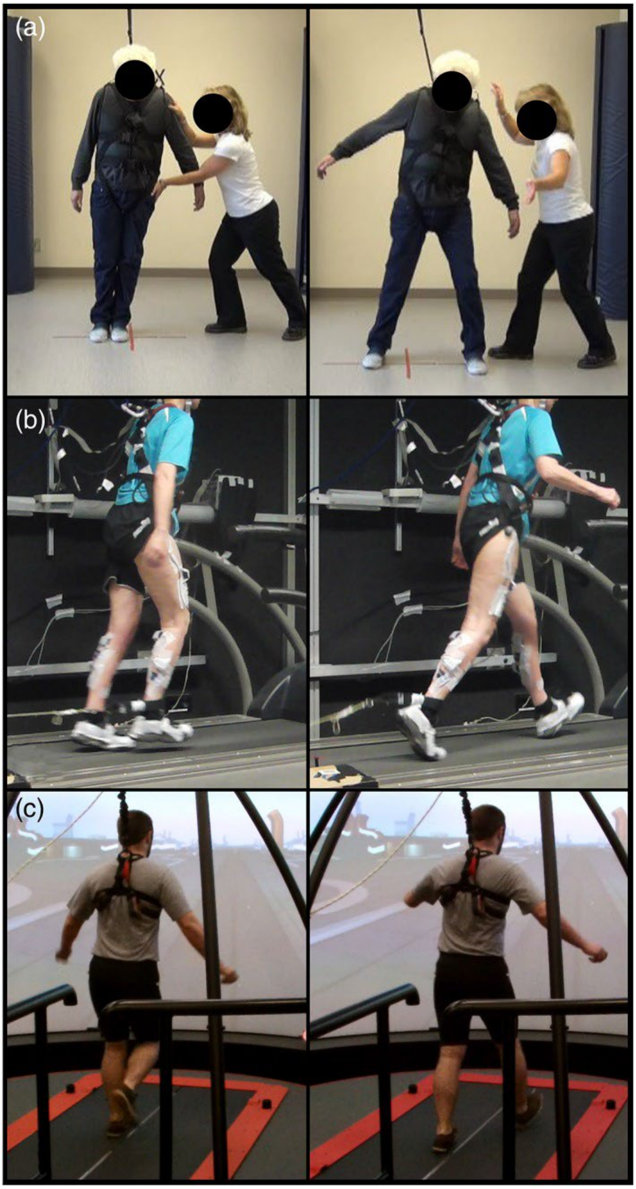

Figure 2.1 Examples of different types of perturbations used in clinical and research settings. (a) A therapist-applied lean-and-release perturbation in the mediolateral direction. (b) A cable trip perturbation on a standard treadmill causing a forward loss of balance. (c) A treadmill belt acceleration perturbation using the Computer Assisted Rehabilitation Environment (Motekforce Link, Amsterdam, the Netherlands), causing a forward loss of balance.

Despite the diminished reactive gait stability seen in older adults in response to a novel perturbation compared with young adults,[25] reactive locomotor adaptation potential (the ability to adapt and improve reactive gait adjustments in a feedback-driven manner) does not appear to decline with age,[26,27] nor does it appear to be specific to one mode (stance, sit-to-stand or gait) of locomotion.[28] By capitalizing on older adults' potential for improvement by providing sufficient and specific stimuli (i.e. PBT), the reactive balance control of older adults could be improved, which might reduce their falls risk. One recent meta-analysis of randomized controlled trials using PBT indeed reported a significantly lower falls incidence in PBT groups after the interventions,[29] with a second meta-analysis combining studies of PBT with voluntary stepping interventions also reporting reduced falls incidence.[30] However, despite this evidence, it is important to consider whether such training is effective and feasible in clinical settings, or whether such benefits are only seen in highly controlled laboratory settings, information that is not yet explored in detail in the literature. Therefore, in the present review, we systematically searched the literature for PBT studies with older adults in order to: (i) examine the characteristics of PBT studies carried out to date with older adults that assessed prospective falls incidence; and (ii) using this evidence from the literature, present and discuss a number of considerations for applying PBT in clinical settings, such as the perturbation characteristics (type, direction, magnitude etc.) and the training program (frequency, volume), that could affect the feasibility and effectiveness of PBT for falls reduction among older adults in clinical settings.

Methods

A systematic literature search with search terms relating to perturbations, training, falls and age with date of publication set at 2002 or later was carried out in PubMed and Web of Science databases (see **Supplemental File 2.1** for the full search strategy). Studies were selected for inclusion if they carried out PBT with older adults (mean age of ≥60 years), reported post-intervention falls data and if a control group was included. Studies that carried out PBT, but that did not provide specific details on the intervention, were excluded from the main synthesis. The final search was carried out on 9 January 2017. Additionally, reference lists of the discovered articles, previous reviews and other articles known to the authors were checked. Studies with healthy older adults, high risk or frail older adults, as well as older adults with neurological disorders that met the above criteria, were considered in the current review.

Results and discussion

The complete search and inclusion process can be seen in **Figure 2.2**. The search yielded 802 records, and four articles were identified through other sources. After removing duplicates, 672 titles were screened. The title screening excluded 489 records, after which the remaining 183 abstracts were assessed for inclusion. A total of 32 full texts were then assessed, and eight articles met all inclusion criteria. The reasons for exclusion at the full text screening stage can be found in **Figure 2.2**. A summary of all included articles can be found in **Table 2.1**.

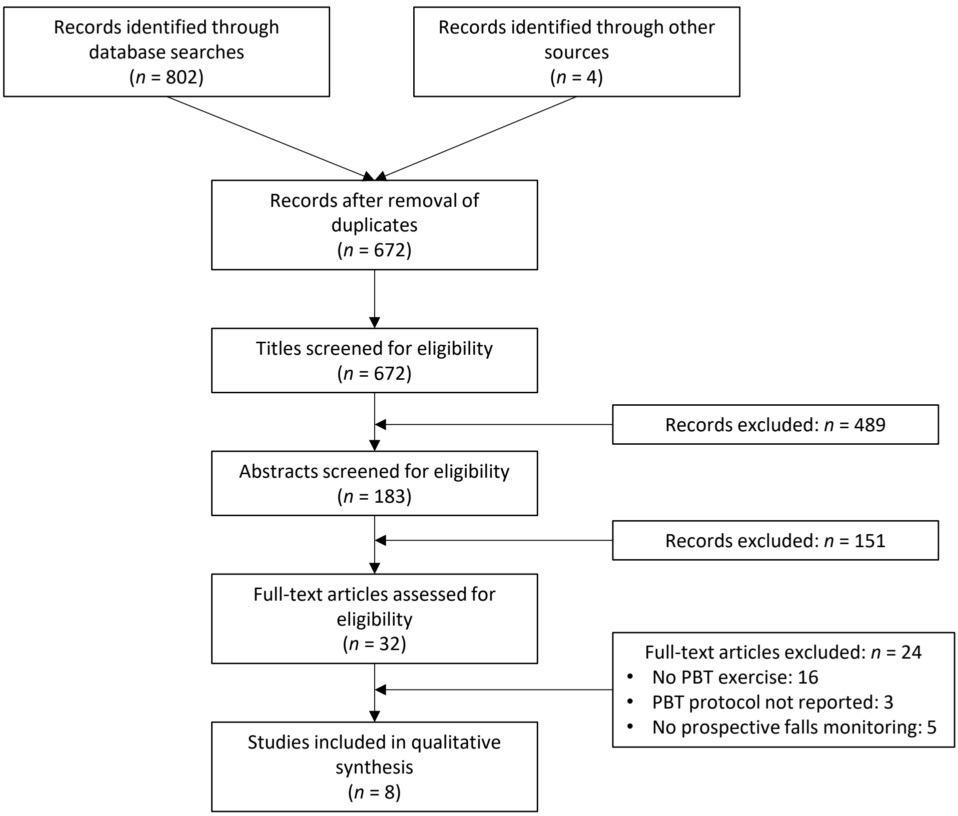

Figure 2.2 Flowchart of systematic search and article inclusion and exclusion process. PBT, perturbation-based balance training.

Table 2.1 Overview of included studies that administered perturbation-based balance training to older adults.

Study	Design	Participants	Perturbation type	Protocol	Falls monitoring	Main outcome
Mansfield *e t al.*[19]	RCT	Healthy, *n*=16, 70.3 years (4.7 years)	Moveable platform in four directions	3 × 30 min/week for 6 weeks	Prospective for 1 year	No significant differences in falls incidence, but not powered for this measure
Pai *et al.*[31]	RCT	Healthy, *n*=67, 72 years (5.5 years)	Moveable platform simulating a slip	1 session of 24 slips	Prospective for 1 year	Intervention led to a significant decrease (34% to 15%) in falls incidence, no change in the control group
Rosenblatt *et al.*[32]	RCT	Healthy, *n*=82, 65.4 years (7.8 years)	Treadmill belt accelerations during standing	4 × 1 h over 2 weeks	Prospective for 1 year	Significantly fewer (17 *vs* 31) likely preventable trip-related falls (17) in the intervention group compared to control group
Lurie *et al.*[34]	Randomized pilot study	High risk, *n*=26, 81.1 years (6.53 years)	Treadmill belt accelerations and decelerations during standing and walking	5.84 sessions of 44.25 min (means)	Retrospective: 3 months preceding and 3 months after the intervention	Non-significant difference in PBT group experiencing falls (19% *vs* 33%) and injurious falls (8% *vs* 18%) compared with controls
Shimada *et al.*[33]	RCT	High risk, *n*=15, 81.8 years (5.9 years) †	Treadmill belt decelerations during walking	600 min of PBT over 6 months	Prospective for 6 months	Non-statistically significant decrease (21%) in falls in the PBT group
Protas *et al.*[35]	RCT	Parkinson's disease, *n*=9, 71.3 years (7.4 years)	Treadmill belt accelerations during standing while facing and sideways	3× per week for 8 weeks.	Prospective: 2 weeks preceding and 2 weeks after the intervention	The PBT group experienced a significant reduction in falls in the 2 weeks after the training period, in comparison to the 2 weeks before the training
Shen and Mak[36]	RCT	Parkinson's disease, *n*=22, 63.3 years (8.0 years)	Treadmill belt accelerations during stance and therapist pushes during walking	3–5× per week for 12 weeks of balance training incorporating PBT	Prospective: 12 months after the intervention	Significantly fewer falls during follow up in the PBT group than in the control group
Smania *et al.*[37]	RCT	Parkinson's disease, *n*=28, 67.64 years (7.41 years)	Standing on foam and moveable platforms while a therapist pulled the participant	3 × 50mins of balance training with PBT, per week for 7 weeks	Retrospective: 1 month preceding, during and 1 month after the intervention	Significant reduction in falls during and a non-significant reduction after the intervention in PBT group. The PBT group experienced significantly fewer falls than controls both during and after PBT.

† Age data from all participants who started the intervention (n=18), just 15 completed the study. PBT, perturbation-based balance training; RCT, randomized controlled trial.

PBT and falls reduction

Three PBT studies have been carried out with healthy, community-dwelling older adults that prospectively monitored falls and included a control group.[19,31,32] Rosenblatt *et al*. examined the effects of PBT on the falls incidence over 1 year of 82 community-dwelling women (mean age 65.4 ears, SD 7.8 years) who received 2 weeks (four 1-h sessions) of PBT (treadmill accelerations) compared with a control group.[32] During the 1-year follow up, the control group (n=80) experienced 31 likely preventable trip-related falls (i.e. compensatory stepping was possible), compared with a significantly lower 17 likely preventable trip-related falls in the intervention group.[32] Pai *et al*. also found a significant reduction in falls incidence after PBT in their study (67 community-dwelling older adults completed the PBT and 1-year follow up; mean age 72 years, SD 5.5 years).[31] Participants were exposed to either just one slip or a single PBT session of 24 unannounced slips. During the follow-up period of 12 months, the intervention group had a 50% decrease (34% to 15%, $P<0.05$) in falls incidence, whereas no change in falls incidence was seen in the control group, who were 2.3-fold more likely to fall than those in the intervention group in the 12-month follow-up period.[31] Finally, Mansfield *et al*. examined the effects of PBT over 6 weeks using a moveable platform during stance to train stepping and grasping reactions in older adults, and found beneficial effects on balance recovery responses to laboratory-based perturbations.[19] The original publication did not report falls data, but prospective falls data were recorded (reported in Mansfield *et al.*[29]). These data did not show significant reductions in falls incidence; however, the study was not powered for this outcome measure.

Two studies have examined the effects of PBT on falls incidence among frail or high-risk older adults.[33,34] Shimada *et al*. examined the effects of adding 600 min of PBT to an existing 6-month physical exercise intervention consisting of balance, strength, endurance, and pain-relieving exercises on falls incidence in a group of 15 long-term care facility residents and outpatients at a high risk of falling (4 were patients with Parkinson's disease, 4 were patients who had strokes, 8 were patients with knee osteoarthritis, the remaining 16 had no specific diagnosis).[33] Participants were randomized to the normal exercise intervention or PBT plus the normal intervention. During the 6-month follow-up period, the number of falls was 21% lower in the intervention group than in the control group, which despite being clinically relevant, was not statistically significantly different (P=0.384) to the control group.[33] Lurie *et al*. found similar results in 31 older adults who were referred to a physiotherapist for gait and balance training.[34] They compared the results of PBT in addition to regular physiotherapy with a control group that received regular physiotherapy consisting of strength, mobility and balance exercises. During the 3-month follow-up period, fewer participants in the intervention group experienced falls (19.23% *vs.* 33.33%, P=0.227) and injurious falls (7.69% *vs.* 18.18%, P=0.243) in comparison with the control group.[34] As with Shimada *et al.*, these results were not statistically significant, despite the clinically relevant differences.[33] However, this was a pilot study, and was not powered to detect differences in falls incidence. Additionally, the 3-month follow-up period might have been too short to detect significant differences.

Three studies have examined the effects of PBT on the incidence of falls in daily life among older adults with Parkinson's disease.[35-37] We do not discuss the above-detailed study of Shimada *et al*. here, as only a proportion of the participants had a neurological disorder.[33] Protas *et al*. investigated the effects of 8 weeks' PBT, in combination with gait training, in nine men with mild-to-moderate idiopathic Parkinson's disease, and showed a significant reduction of falls in the 2 weeks after the training period, in comparison with the 2 weeks before the training.[35] Smania *et al*. carried out a similar study in 28 older adults with moderate-to-severe Parkinson's disease.[37] In that study, 7 weeks' balance training incorporating PBT was compared with general physical exercise for effects on falls incidence during, and for 1 month after, the intervention.[37] PBT led to a significant reduction in falls during and a non-significant reduction after the intervention compared with the month before.[37] In comparison with the control group, the PBT group experienced significantly fewer falls both during and after the intervention.[37] Finally, Shen and Mak reported significantly fewer falls in older adults with mild-to-moderate Parkinson's disease during a 15-month follow up after 3 months' balance training including PBT, compared with participants who had completed strength training.[36] Although the results of these studies suggest a beneficial effect of PBT on falls risk in Parkinson's disease, all of the interventions had multiple components, only one of which was PBT, and therefore, the exact effect of PBT is difficult to determine. That being said, one recent study showed that people with Parkinson's disease can adapt their reactive dynamic stability control after perturbations to stance, and retain motor adaptations to a similar degree as healthy older adults over 24 h.[38] This suggests that reactive adaptation might not be completely inhibited in Parkinson's disease, which is promising for the clinical implementation of PBT in this patient group.

There has been less research carried out on PBT in other patient populations. One study of the effects of PBT on falls post-training in people with chronic stroke is currently underway.[39] Preliminary results from another non-randomized study including individuals with subacute stroke show a trend for reduced falls in daily life after PBT.[40] In both of the previous stroke studies, a physiotherapist applied perturbations through pushes and nudges. One other previous study of people with chronic stroke incorporated similar PBT exercises into an agility-based training program.[41] A reduced number of falls during laboratory-based platform perturbations was observed after PBT, but no differences were seen in daily life falls incidence, probably as a result of the study not being powered for this outcome measure.[41] Despite these promising results, more research is required to determine the effectiveness and feasibility of PBT for falls reduction in patient groups with an increased falls risk.

Implementing PBT in clinical practice

In this section, we discuss a number of factors that should be considered when implementing PBT in clinical practice. This is done with reference to current research in both laboratory and clinical settings. The included studies in the present review, as well as studies analyzing the effects of PBT on reactive compensatory stepping behavior after laboratory-based perturbations are discussed, as the effects of PBT can be evaluated more precisely in such laboratory settings.

PBT setups in clinical practice

Although many methods are available for delivering unexpected perturbations, the PBT studies that have been carried out in clinical settings have generally opted for treadmill-based perturbations[33-36,42] or therapist-applied perturbations.[39-41] There are two practical advantages to treadmill-based setups: the lack of required space and the relative ease of securing a fixed harness system above the treadmill. These studies have used treadmill belt accelerations during stance or walking in order to perturb the participant's balance in a similar manner to a trip or a slip, and this setup appears to be feasible in clinical settings.[34] Therapist-applied perturbations could be considered the most clinically feasible type of perturbations, given the low cost and limited equipment required. These can be either internal perturbations (having the patient carry out a task that causes instability) or external perturbations. External therapist-applied perturbations can include lean-and-release or pushing and pulling the participant in multiple directions.[39] The feasibility of PBT in clinical settings is also supported by case studies of patients with progressive supranuclear palsy[42] and subacute stroke[43] reporting positive outcomes. Once the most feasible setup for PBT has been determined, it is important to consider how to best maximize the effects of PBT.

Maximizing long-term effects of PBT

One key factor that might determine how successful PBT can be for reducing falls is the extent to which participants retain improvements in reactive balance control they have made during training over the weeks, months and years after training. In PBT studies, the long-term effects can be determined through prospective falls monitoring or perturbation recovery performance assessed in a laboratory setting. These improvements could be enhanced ability to increase the base of support by stepping, decreased reaction time to perturbations or improved counter rotation to control the center of mass.[18,44] This retention can be affected by a combination of the perturbation type and magnitude, but also the training volume. Previous studies reported that both healthy older adults and patients with Parkinson's disease, after experiencing a single session of perturbations, showed at least partial retention of reactive balance control improvements over short periods of 24 h.[27,38] Studies with healthy older adults have also shown retention over longer periods of 6,[45,46] 9 and 12 months[46] in laboratory settings. Retention in compensatory step length has also been shown in patients with Parkinson's up to 2 months after a 2-week long PBT intervention.[47] Retention over such long time periods indicates that PBT provides a strong stimulus for the neuromuscular system, which could indicate that high training volumes might not be necessary to maximize retention. Bhatt *et al*. also investigated the effect of experiencing a single slip perturbation 3 months after a perturbation session on retention at 6 months.[45] Their results show that such a “booster” session helped participants to retain improvements in reactive balance control.[45] These findings are potentially important for clinical practice, as they show that after an initial training period, long-term retention of the benefits of PBT is possible and can be enhanced with short additional sessions.

Perturbation magnitudes

One way to maximize the effects of PBT is to use perturbations of appropriate magnitude. In the aforementioned studies, a variety of magnitudes were used, that were either fixed or progressive with training. High-magnitude perturbations, where participants initially require support from the harness to regain stability, appear to trigger fast and significant adaptation in recovery behavior, and long-term retention of motor adaptations.[31,45,46,48] However, studies based in clinical settings have generally used a more progressive increase in perturbation magnitude, starting with lower-magnitude perturbations and progressing based on the supervising physiotherapist's judgement.[34,37] Although perturbation magnitudes that result in participants requiring support from the harness have been shown to be effective, these might not always be appropriate for specific groups, such as frail older adults or people with neurological conditions, as physical injury is possible even if the safety harness is used to prevent a fall to the floor. Additionally, high-magnitude perturbations might not be tolerated by some frail individuals, which could increase withdrawal from the program. It is not yet clear how much perturbation magnitude impacts motor learning and retention. In young adults, exposure to smaller-magnitude perturbations can improve stability control after larger-magnitude perturbations.[49] However, it has also been shown that younger adults can recover more effectively from an overground slip after high-, rather than low-, magnitude perturbation experience.[50] Given the mixed evidence in young adults, and the benefits of both approaches shown in older adults, selecting perturbation magnitudes that are safe and tolerable while still challenging for the participant appears to be a reasonable choice for clinical applications.

Perturbation directions

Second to the perturbation magnitude, the direction of perturbation should be considered. In the studies discussed above, two studies applied perturbations that caused a loss of balance in the backward direction.[31,33] Another study applied only perturbations leading to a forward loss of balance,[32] whereas three studies applied perturbations in both directions.[34-36] Although the impact of perturbation direction on falls incidence or types of falls experienced is not known, there is evidence to suggest that adaptation to perturbations in one direction might not transfer and benefit reactive balance control in another direction.[27,38] Perturbations in the mediolateral directions should also be considered when applying PBT in clinical settings, because of the reduced mediolateral stability seen in older adults.[51] This reduced mediolateral stability can also be seen during forward compensatory stepping, where older adults often struggle to stabilize the leg, and keep from falling sideways.[52,53] Although repetition of one single perturbation might improve certain mechanisms of balance control that can be transferred to other tasks (e.g. counter rotations or rapid stepping to enlarge the base of support), it seems reasonable to suggest that multidirectional perturbations that target several balance recovery strategies might be the most advantageous for falls reduction in older adults.

PBT frequency and volume

The optimal frequency and volume of PBT for falls reduction among older adults must be considered. Although the duration of training sessions in previous studies has not always been described, most report sessions of 50 min to 1 h. The frequency and training load varies to a greater extent from just single sessions to multiple sessions over a number of months. It is important for future research to determine the minimum effective dose for falls reduction in different participant and patient groups, as this would minimize the time and financial commitment required for PBT in clinical settings. As aforementioned, this might depend on the magnitude of perturbations used. With high-magnitude perturbations, relatively low PBT volume might be required for long-term benefits.[31,45,46,48] With lower-magnitude perturbations, which might be more feasible with frail, older adults or different patient groups, longer training periods might be required in order to result in a significant reduction in falls incidence.

Other considerations

Falls tend to occur in daily life during execution of movement (e.g. walking or transferring from standing to sitting), and rarely occur during quiet standing.[1,54,55] Therefore, perturbations should be applied during tasks, such as walking,[33,34] weight shifting[39,56] and rising from a chair.[57] Falls can also occur in varied environmental circumstances that pose sensory and mechanical challenges to balance control (e.g. in the dark/dim light or in the presence of obstacles that impede stepping), and can occur when the individual is distracted. Therefore, PBT programs should consider adding sensory, environmental and cognitive challenges during training to help to promote generalizability of improved reactive balance control to realistic situations.[39,57]

Future research directions

Based on the PBT studies discussed in the present review, a number of methodological issues should be addressed in the future. First, the intervention was not always standardized across participants because of the individualization based on ability and physiotherapist judgement.[33,34,36,37] Although these studies showed the feasibility of PBT in clinical practice, conclusions related to the optimal perturbation number and type are difficult to make. Second, the falls monitoring follow-up period differed between studies, with four studies following participants for 6 or 12 months, and three studies with a follow-up period between 1 and 3 months. This makes comparisons across different interventions more difficult with regard to long-term benefits of PBT. As these interventions differed greatly and were carried out in different subject groups, it is difficult to determine the components of PBT that affect long-term retention in PBT-induced adaptations. Therefore, more controlled studies of PBT with long-term follow up are required to better determine the effects of different PBT components on motor adaptation, retention and falls.

Conclusion

PBT appears to be a feasible approach to reducing falls among older adults in clinical settings. Based on the current evidence, it appears that treadmill-based systems and therapist-applied perturbations might be the most practical methods in clinical settings, and PBT that incorporates multiple perturbation types and directions might be of most benefit.

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Supplemental file 2.1 Search Strategy

PubMed Search on 09/01/2017:
((((((Perturb*[Title/Abstract] OR trip[Title/Abstract] OR slip*[Title/Abstract] OR dynamic balanc*[Title/Abstract])) AND (train*[Title/Abstract] OR exercis*[Title/Abstract] OR rehabilitation[Title/Abstract])) AND falls[Title/Abstract]) AND (Age[Title/Abstract] OR aged[Title/Abstract] OR elderly[Title/Abstract] OR older[Title/Abstract])) NOT review[Publication Type]) AND ("2002"[Date - Publication] : "3000"[Date - Publication])
Search returned: 157 results

Web of Science on 09/01/2017:
((TS=(Perturb* OR trip OR slip* OR dynamic balanc*) AND TS=(train* OR exercis* OR rehabilitation) AND TS=falls AND TS=(Age OR aged OR elderly OR older)) OR (TI=(Perturb* OR trip OR slip* OR dynamic balanc*) AND TI=(train* OR exercis* OR rehabilitation) AND TI=falls AND TI=(Age OR aged OR elderly OR older))) *AND* DOCUMENT TYPES: (Article)
Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI Timespan=2002-2017
Search returned: 645 results

Records identified through database searches: 802 records

3

Adaptability to balance perturbations during walking as a potential marker of falls history in older adults

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Abstract

Given that falls most commonly occur during walking due to unexpected balance perturbations like trips and slips, walking-based balance assessment including walking stability and adaptability to such perturbations could be beneficial for fall risk assessment in older adults.

This cross-sectional study reanalyzed data from two larger studies conducted with the same walking protocol. Participants completed unperturbed walking trials at speeds of 0.4 m/s up to 1.8 m/s in 0.2 m/s steps. Ten unannounced treadmill belt acceleration perturbations were then applied while participants walked at equivalent stability, assessed using the margins of stability. Retrospective (12 months) falls incidence was collected to divide participants into people with and without a history of falls.

Twenty older adults (mean age 70.2±2.9 years) were included in this analysis; 8 people with one or more recent falls and 12 people without, closely matched by sex, age and height. No significant differences were found in unperturbed walking parameters or their variability. Overall perturbation-recovery step behavior differed slightly (not statistically significant) between the groups after the first perturbation and differences became more pronounced and significant after repetition of perturbations. The non-faller group significantly reduced the number of recovery steps needed across the trials, whereas the faller group did not show these improvements.

Fallers tended to have slightly delayed and more variable recovery responses after perturbation compared to non-fallers. Non-fallers demonstrate more signs of adaptability to repeated perturbations.

Adaptability may give a broader indication of the ability of the locomotor system to respond and improve responses to sudden walking perturbations than unperturbed walking variability or recovery to a single novel perturbation. Adaptability may thus be a more useful indicator of fall risk in older adults and should be considered in further research.

Background

Falls are a principal cause of injury, leading to disability and hospitalization in older adults.[1] Therefore, adequate identification and treatment of older fallers are critical. Approximately 60% of outdoor falls in older adults occur when unexpected balance perturbations during walking (e.g. slips or trips) cause a sudden change in the relationship between the center of mass (CoM) and base of support (BoS) of the body.[2] Thus, balance assessment during walking, focusing on walking stability and adaptability may be beneficial for fall risk assessment in older adults.[3-5]

In response to balance perturbations such as slips and trips, older adults show less effective initial recovery responses than younger adults.[6-8] Still, the literature reports that older adults seem fully capable of improving their responses when exposed to repeated perturbations.[9-11] As a result, walking stability in response to single and repeated perturbations may capture different underlying mechanisms. However, how adaptability to repeated perturbations relates to real life falls has not been the topic of many studies. Pai et al.[4] associated adaptability to repeated slip perturbations during a sit-to-stand task with a lower likelihood of future falls in daily life in older adults. Adaptability was indicated by less balance loss and falls during the task and improved recovery performance during the final slip. This association has not yet been thoroughly investigated for mechanical perturbations during walking, which are more task-specific to the most common causes of falls in older adults.

In this study, we aim to address the extent to which stability following a single perturbation and adaptability following repeated perturbations relate to falls history in older adults. Stability of the body configuration during walking will be measured using the margin of stability (MoS).[12] Due to previous indications of differences between older adults with and without a history of falls[13,14] we also analyze step variability during unperturbed walking, to examine how these potential differences relate to those seen in the perturbation tasks. These analyses may give indications of the usefulness of such tasks and properties for falls risk assessments and falls prevention. We hypothesize that there will be not only higher step variability during walking, but also a reduced ability to cope with and adapt to unexpected balance perturbations during walking in older adults who fell in the past 12 months compared to older adults who did not fall.

Methods

Setting and subjects

This cross-sectional study reanalyzed data from two larger studies that included the same walking protocol.[15,16] Older adults were recruited from the city of Maastricht, the Netherlands, and the surrounding area. Inclusion criteria were; community-dwelling, 65 to 80 years old, no known musculoskeletal or neurological deficits and no history of dizziness, balance or walking complaints. All subjects provided written informed consent. Both studies were approved by the medical ethics committee (METC) at Maastricht University Medical Centre (MUMC+) (NL58205.068.16 & NL59895.069.17) and were conducted in accordance with the declaration of Helsinki. Prior to the walking measurements, participants were given a short falls history questionnaire based on the recommendations of Lamb et al. and Lord et al.[17,18], that led with the question: “In the past year, have you had any fall including a slip or trip in which you lost your balance and landed on the floor or ground or lower level?” This was followed by other questions about the number, location and cause of the fall(s) and about any injuries sustained. The questionnaire is available from https://osf.io/hmjef/.[19] Participants were divided into two groups based on their answers to this questionnaire. The Falls group including those participants who reported one or more falls in the past year, and the No-Falls group including those who did not fall.

For the current secondary analysis, a sample size calculation was conducted to determine the required sample size for α=0.05, β=0.8 and estimated effect size of f=0.5 for the group effect (falls history vs. no falls history) on MoS in a two-way ANOVA, with step as the other (repeated measures) factor (Baseline, pre-perturbation and the first eight recovery steps). This effect size for the MoS across the steps corresponds to a Cohen’s *d* of 1 and to an approximately three-step difference in recovery to baseline MoS based on previous analyses[15], which we interpret to be clinically meaningful. This revealed a required total sample of 20 participants. All available fallers from the existing datasets were included in the reanalysis, and a group of non-fallers was formed from participants who most closely matched the fallers in sex, age, and height.

Setup

Measurements were conducted with the Computer Assisted Rehabilitation Environment Extended (CAREN; Motekforce Link, Amsterdam). This comprises of a dual-belt force plate-instrumented treadmill (1000Hz), a 12 camera Vicon Nexus motion capture system (100Hz; Vicon Motion Systems, Oxford, UK) and a 180° virtual environment providing optic flow. A safety harness connected to an overhead frame was worn by the participants. Six retroflective markers were attached to anatomical landmarks (C7, sacrum, left and right trochanter and left and right hallux) to calculate MoS.

Procedures

Participants completed familiarization trials followed by measurement trials from speeds of 0.4m/s up to 1.8m/s in 0.2m/s steps. To ensure equivalent stability across participants and groups during the perturbation trials, the stability-normalized walking speed was then calculated using the mean anteroposterior MoS of the final 10 steps of each walking trial (0.4m/s to 1.8m/s)[20]). The method and effectiveness of this approach are described in detail elsewhere.[20] For each participant, the walking speed that would result in MoS of 0.05m was calculated. The walking perturbation protocol then began with participants walking at the stability-normalized speed for 3-4 minutes, followed by 10 unilateral treadmill belt acceleration perturbations, which occurred unannounced every 30-90 seconds. The perturbation was a 3 m/s^2 acceleration of the treadmill belt to a maximum speed equal to 180% of the stability-normalized walking speed. The acceleration began when the hallux marker of the to-be-perturbed limb passed the hallux marker of the opposite foot in the sagittal plane. The belt decelerated at toe-off of the perturbed limb. Participants were naïve to the specifics of the perturbation protocol (i.e. limb, type, number, timing, magnitude). The first and tenth accelerations perturbed the right leg, while the second to ninth accelerations perturbed the left leg. This way, not only balance recovery after a novel perturbation, but also adaptation to repeated perturbations can be studied within the same protocol. A schematic overview of the perturbation protocol is shown in **Figure 3.1**. Further technical details of the perturbations can be found elsewhere.[21]

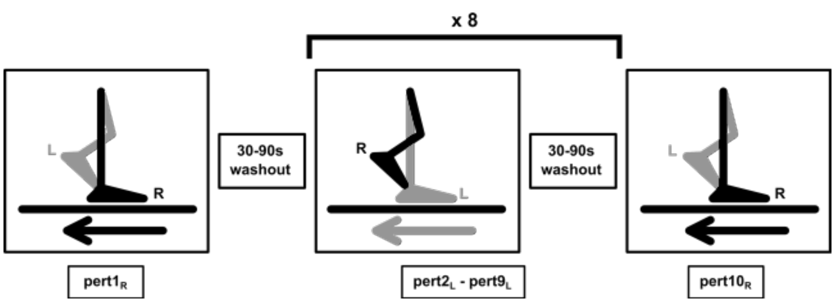

Figure 3.1 Gait perturbation protocol [image previously shown in McCrum *et al*. (2019b)]. The right leg (R) was perturbed by the treadmill belt acceleration first (Pert1R), followed by eight perturbations (Pert2L – Pert9L) to the left leg (L), and the final perturbation (Pert10R) was again applied to the right leg (R). In all, 30–90 s of unperturbed walking occurred between each perturbation. The perturbation was designed to cause a forward rotation and acceleration of the upper body, relative to the lower body, leading to a forward loss of dynamic stability.

Data processing

Data processing was conducted in MATLAB (2016a, The MathWorks, Inc., Natick). The three-dimensional coordinates of the markers were filtered using a low pass second order Butterworth filter (zero-phase) with a 12Hz cut-off frequency. Foot touchdown and toe-off were detected using marker and force plate data, as described previously.[22] The anteroposterior MoS at foot touchdown were calculated as the anteroposterior distance between the anterior boundary of the base of support (BoS) and the extrapolated center of mass, adapted for our validated reduced kinematic model.[12,23] The MoS was calculated for the following steps: baseline for each perturbation was the mean MoS of the eleventh to second last step before each perturbation (Base); the final step before each perturbation (Pre); and the first eight recovery steps following each perturbation (Post1-8). The number of steps to return to baseline stability following the perturbation was determined by calculating the number of steps that were within 0.05m of the MoS value of Base for each individual, counting back from the eighth recovery step, using custom written R code (R version 3.6.0;[24]). Additionally, the means and coefficients of variation of step length, width and time, as well as double support time, were calculated using the foot marker data for 0.4, 0.8, 1.2 and 1.6 m/s unperturbed walking trials.

Analysis

The effects of falls history on MoS recovery after the first perturbation to each leg ($Pert1_R$ and $Pert2_L$; representing the un-adapted response) and the final perturbation to the left leg ($Pert9_L$; representing the adapted response), were analyzed using repeated-measures two-way ANOVA with group (Falls/No-Falls) and step (repeated measures: Base, Pre, Post1-8) as factors for each of the perturbations separately. Additionally, Mann-Whitney tests were applied to compare the groups on number of recovery steps needed for each perturbation and Friedman tests were used to assess the change in steps across perturbations within each group. Finally, the spatial (step length and width means and variability) and temporal (step and double support time means and variability) parameters of gait at a range of walking speeds (0.4, 0.8, 1.2 and 1.6 m/s) were compared between the Falls and No-Falls groups using a two-way ANOVA with group (Falls/No-Falls) and walking speed (repeated measure) as factors.

Results

Twenty older adults (8 with, and 12 without falls in the previous year) were included in this study. Characteristics of participants described by group (Falls/No-Falls) can be found in **Table 3.1**: participant characteristics. Six of the eight participants in the Falls group fell only once in the previous year, one reported two falls, and one fell three or more times.

Table 3.1 Participant characteristics (mean ± SD).

	Falls group	No-Falls group
Men/Women (n)	4/4	6/6
Age (years)	70.6±3.6	70±2.4
Height (cm)	168.2±15.4	169.4±7.2
Weight (kg)	75±16.3	75.6±10.3
Body Mass Index	26.3±3.3	26.3±2.9
Stability-normalized walking speed (m/s)	1.29±0.13	1.31±0.14
Falls in the previous year n (frequency)	1 (6), 2 (1), ≥3 (1)	0 (12)

Step parameters

Spatial and temporal parameters of gait, as well as their variability, were compared between groups using two-way repeated-measures ANOVAs. From these analyses, no significant effects of group (Falls vs. No-Falls), and no interaction effects (Group x Speed) were found for any parameter (the complete effect and interaction results can be found in **Supplemental file 3.1**).

Stability and adaptability

All participants were able to recover from the walking perturbations without harness assistance. However, due to a technical failure during the first perturbation, one participant was excluded from the analyses involving $Pert1_R$. Two-way repeated-measures ANOVAs for $Pert1_R$, $Pert2_L$ and $Pert9_L$ did not reveal significant effects of falls history on MoS ($Pert1_R$: $F_{(1,\ 17)}$=0.89, P=0.36; $Pert2_L$: $F_{(1,\ 18)}$=3.07, P=0.097; $Pert9_L$: $F_{(1,\ 18)}$=3.3, P=0.085). Significant step by falls history interaction effects on MoS were found for $Pert2_L$ and $Pert9_L$ ($Pert1_R$: $F_{(9,\ 153)}$=0.31, P=0.97; $Pert2_L$: $F_{(9,\ 162)}$=5.25, P<0.0001; $Pert9_L$: $F_{(9,\ 162)}$=3.63, P=0.0004). Dunnett's tests for multiple comparisons were used to compare the MoS for each step to the Base value (results indicated in **Figure 3.2**). Sidak's tests for multiple comparisons were used to compare the MoS between groups and revealed that only Post2 in $Pert2_L$ was significantly different (**Figure 3.2**; note that the study was not powered for these pairwise comparisons). Complete Dunnett and Sidak results can be found in the supplementary material.

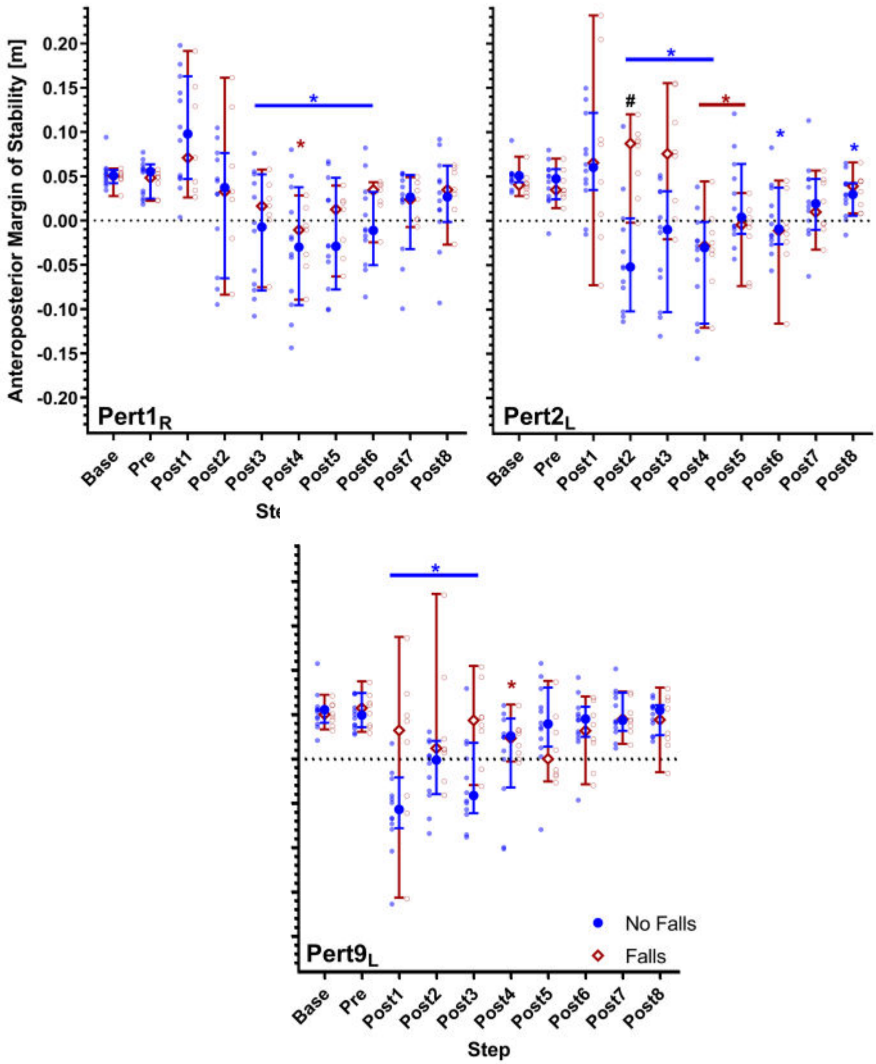

Figure 3.2 Median and 95% confidence intervals (with individual data points) of the anteroposterior margins of stability during the first, second and ninth perturbations ($Pert1_R$, $Pert2_L$, and $Pert9_L$, respectively) including unperturbed walking prior to each perturbation (Base), the final step prior to each perturbation (Pre) and the first eight recovery steps following the perturbations (Post1–8) for Falls and No-Falls groups. Blue * and Red *: significant difference to Base for the No Falls and Falls groups, respectively (P<0.05; adjusted using Dunnett's multiple comparisons test). #: significant difference between the No-Falls and Falls groups (P<0.05; adjusted using Sidak's multiple comparisons test).

The Falls group required averages of 6.3, 5.6 and 5.4 recovery steps and the No Falls group required averages of 6.4, 6.6, and 4.4 recovery steps for $Pert1_R$, $Pert2_L$, and $Pert9_L$, respectively (see **Figure 3.3**). Mann-Whitney tests did not find significant group differences in number of recovery steps ($U=37$, $P=0.7$; $U=37.5$, $P=0.44$; $U=31$, $P=0.19$). A Friedman test revealed a significant effect of perturbation number on the number of recovery steps in the No Falls group (Friedman statistic=12.41, $P=0.002$), with Dunnett's multiple comparisons tests revealing significant differences between $Pert9_L$ and both $Pert1_R$ ($P=0.018$) and $Pert2_L$ ($P=0.007$). Due to the missing participant in the Falls group at $Pert1_R$, Wilcoxon signed rank tests were used for this group and did not reveal significant differences in the number of recovery steps needed between $Pert1_R$ and $Pert2_L$ ($P=0.25$), $Pert1_R$ and $Pert9_L$ ($P=0.53$) and $Pert2_L$ and $Pert9_L$ ($P>0.99$).

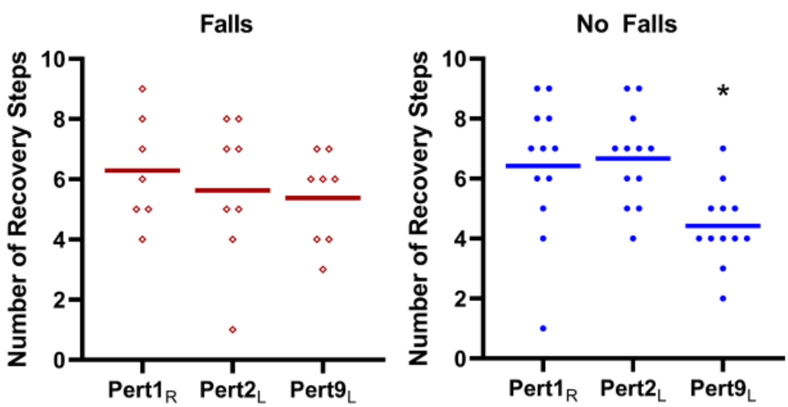

Figure 3.3 The number of recovery steps (means and individual values) required by the Falls group (left panel) and No Falls group (right panel) for the first, second and ninth perturbations ($Pert1_R$, $Pert2_L$, and $Pert9_L$, respectively). *: Significant difference to $Pert1_R$ and $Pert2_L$.

Discussion

The aim of this study was to address the extent to which walking stability following a single perturbation and walking adaptability following repeated perturbations relate to falls history in older adults. We hypothesized that older adults with a history of falls would demonstrate decreased stability and adaptability compared to older adults without a history of falls. Additionally, we analyzed step variability during unperturbed walking, due to previous indications of increased variability in older adults with a history of falls.[13]

Previous studies indicate differences in variability during unperturbed walking between older adults with and without a history of falls (for a review see[13]). However, in this study, no significant between-group differences in variability during unperturbed walking were found. Our study used set walking speeds instead of self-selected walking speeds, which may have resulted in differences compared to previous studies (7 out of the 13 studies reviewed in[13] that found significant differences between fallers and non-fallers do not mention accounting for walking speed). The results of this study (**Supplemental file 3.1**) show significant walking speed effects on nearly all parameters, but no significant group effects.

Our results showed no significant effects of falls history on MoS during the first left or right leg perturbations ($Pert1_R$ and $Pert2_L$). However, significant step by falls history interaction effects on MoS were found for $Pert2_L$, with a significant between-group difference in the second recovery step. The middle panel in **Figure 3.2** shows that the No-Falls group had negative MoS on the second recovery step, while the Falls group still had positive MoS. This may be due to a difference in the recovery response directly after the perturbation, in which the Falls group shows a slightly delayed recovery compared to the No-Falls group. These differences are less pronounced but consistent with findings from another study[15], which compared reactive stability between healthy young and older adults using the same walking perturbation protocol. In that study, older adults had a more posterior extrapolated center of mass in response to the perturbation, resulting in initially more positive MoS but a delayed stability recovery. Additionally, notably greater inconsistency in perturbation recovery responses across the Falls group compared to the No-Falls group can be observed in **Figure 3.2**, indicating there may be inconsistent recovery strategies in older adults with a history of falls. Despite more inconsistency however, the highest MoS value in the first recovery steps consistently belongs to participants in the Falls group. Combined, these results might hint at a decreased ability to coordinate the dual tasks of maintaining stability and continuing walking on the treadmill with age, and a further decrease in older adults with a history of falls compared with older non-fallers. This is consistent with findings from a study by dos Santos et al, which suggested a tendency for older fallers to favor a ‘stability-first’ strategy, when facing other motor dual-tasks.[25] In their study, older fallers showed similar walking stability but decreased accuracy when placing a dowel over a target compared to non-fallers. The differences between the Falls and No-Falls groups after the first perturbation found in this study, are insufficiently pronounced to be a useful indicator of falls risk. However, corroborated with the presented literature, they suggest that the ability to coordinate a physical dual-task (combined stability recovery after a walking perturbation and continued treadmill walking) may be related to fall risk in older adults. To clarify this relationship and how it relates to daily-life situations of older adults, future studies may focus on the ability to coordinate various dual-tasks with stability recovery from perturbations during overground walking.

While the results showed no significant group effect, a significant step by falls history interaction on MoS was found for the last left leg perturbation ($Pert9_L$). This indicates a difference between the groups for specific steps after this perturbation. Additionally, high variation in MoS after $Pert9_L$ in the Falls group is observed (indicated by the wider confidence intervals and individual data points), as there was during the early perturbations, and the presence of some high MoS values in the first recovery steps remains. In contrast, the variability in MoS in the No-Falls group has visibly decreased by $Pert9_L$, and there are no longer any high MoS values in this group in the first few recovery steps. Together, this indicates better adaptation in the No-Falls group, who by $Pert9_L$, seem to respond with more consistent and effective recovery responses. Statistically this is substantiated by the significant differences in the number of recovery steps needed to reach close to normal stability values between perturbation 9 and the first two perturbations in the No-Falls group, with no significant differences in the Falls group. These findings are in alignment with results from a study by Pai et al., who demonstrated that adaptability to repeated perturbations during a sit-to-stand task may give an indication of falls risk.[4] These findings suggest that with further research, adaptation to repeated walking perturbations may be a useful measure to distinguish between older adults with and without a history of falls.

We hypothesize that recovery to a single novel treadmill acceleration perturbation is too specific a task to assess overall fall risk. The task-specificity of balance is now well established[26-28] and given that falls can occur in a multitude of ways, this one specific perturbation might not represent or generalize to all possible causes of falls. Reduced adaptability, however, may give a broader indication of the ability of the locomotor system to respond and improve reactive responses to sudden perturbations, which may better generalize to the many situations that could lead to falls. It may also serve as a marker for the health of the locomotor control system (which may, in turn, be linked with falls risk), as reduced adaptability to such perturbations has often been shown in sensory and neurological pathology[29]. How the proposed relation between adaptability to repeated perturbations, locomotor system health and falls risk presents in daily-life remains unclear, and should be studied further. Additionally, there are many ways that walking adaptability can be assessed, and it is currently unclear if the method of assessment is critical.[30] Further research on walking adaptability in various tasks, including repeated external perturbations such as slips or trips, in older fallers and non-fallers, could help address this gap in knowledge.

We included a relatively healthy sample of older adults, resulting in mostly older adults who had experienced a single fall in the Falls group (with no known musculoskeletal or neurological deficits and no history of dizziness, balance or walking complaints), which may decrease the generalizability of the results to more frail populations. However, it is in this relatively healthy part of the older population where other clinical tests are known to have ceiling effects, which makes it important to determine other methods of indicating increased risk of falls for this population.[31] Having experienced one or more previous falls is one of the strongest predictors for future falls in community-dwelling older adults (OR 2.8 for all fallers; OR 3.5 for recurrent fallers).[32]

In conclusion, this study found some small but significant differences in reactive stability and adaptability between older adults with and without a history of falls, but no differences in variability of unperturbed walking. The results indicate that older adults with a history of falls may have decreased ability to coordinate the dual tasks of regaining stability and continuing to walk on the treadmill. The differences between the groups were more pronounced after repeated perturbations, with evidence of better adaptation in the No-Falls group, while increased variability of recovery responses and signs of a different recovery strategy remained in the Falls group. The results from the present study indicate that further research on adaptability to repeated walking perturbations as an indicator of falls history, and how this presents in the daily life of older adults, is warranted.

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Supplemental file 3.1

Table S3.1 Comparison of Step parameters during unperturbed walking.

Parameter	Effect/Interaction	F (DFn, DFd)	P value
Step Length	*Speed x Group*	F (3, 54) = 0.6776	P=0.5696
	Speed	F (1.506, 27.11) = 858.4	P<0.0001
	Group	F (1, 18) = 0.8355	P=0.3728
Step Length CoV	*Speed x Group*	F (3, 54) = 1.786	P=0.1608
	Speed	F (1.266, 22.79) = 62.39	P<0.0001
	Group	F (1, 18) = 0.2174	P=0.6466
Step Time	*Speed x Group*	F (3, 54) = 1.183	P=0.3250
	Speed	F (1.110, 19.98) = 118.0	P<0.0001
	Group	F (1, 18) = 1.068	P=0.3151
Step Time CoV	*Speed x Group*	F (3, 54) = 0.1514	P=0.9283
	Speed	F (1.287, 23.16) = 83.78	P<0.0001
	Group	F (1, 18) = 0.01653	P=0.8991
Step Width	*Speed x Group*	F (3, 54) = 0.2794	P=0.8400
	Speed	F (2.011, 36.20) = 3.114	P=0.0563
	Group	F (1, 18) = 1.832	P=0.1927
Step Width CoV	*Speed x Group*	F (3, 54) = 0.7028	P=0.5545
	Speed	F (2.102, 37.84) = 14.14	P<0.0001
	Group	F (1, 18) = 0.2798	P=0.6033
Double Support Time	*Speed x Group*	F (3, 54) = 0.9764	P=0.4107
	Speed	F (1.034, 18.62) = 161.3	P<0.0001
	Group	F (1, 18) = 0.1133	P=0.7403
Double Support Time CoV	*Speed x Group*	F (3, 54) = 0.2491	P=0.8617
	Speed	F (1.349, 24.28) = 19.74	P<0.0001
	Group	F (1, 18) = 0.0002750	P=0.9870

Spatial and temporal parameters of gait, as well as their variability during unperturbed walking at various speeds, were compared between groups using two-way repeated-measures ANOVAs. CoV: Coefficient of variation.

Table S3.2 Pairwise comparisons perturbation 1 – Dunnett's multiple comparisons test.

	Mean Diff.	95% CI of diff.	Below threshold?	Summary	Adjusted P Value
No-Falls group					
Base vs. Pre	0,005	-0.008880 to 0.01888	No	ns	0,8176
Base vs. Post1	-0,04769	-0.1110 to 0.01562	No	ns	0,1777
Base vs. Post2	0,03166	-0.02848 to 0.09180	No	ns	0,4883
Base vs. Post3	0,06621	0.008354 to 0.1241	Yes	*	0,0233
Base vs. Post4	0,08393	0.02294 to 0.1449	Yes	**	0,007
Base vs. Post5	0,06883	0.01259 to 0.1251	Yes	*	0,0154
Base vs. Post6	0,05613	0.01637 to 0.09590	Yes	**	0,0058
Base vs. Post7	0,03967	-0.005703 to 0.08504	No	ns	0,0964
Base vs. Post8	0,02932	-0.01495 to 0.07359	No	ns	0,274
Falls group					
Base vs. Pre	0,006029	-0.009982 to 0.02204	No	ns	0,6733
Base vs. Post1	-0,04411	-0.1323 to 0.04413	No	ns	0,4295
Base vs. Post2	0,004845	-0.1164 to 0.1261	No	ns	0,9998
Base vs. Post3	0,03808	-0.02532 to 0.1015	No	ns	0,2819
Base vs. Post4	0,07009	0.01061 to 0.1296	Yes	*	0,0245
Base vs. Post5	0,05296	-0.01004 to 0.1160	No	ns	0,0985
Base vs. Post6	0,0234	-0.01553 to 0.06233	No	ns	0,2814
Base vs. Post7	0,02757	-0.009917 to 0.06506	No	ns	0,1561
Base vs. Post8	0,01598	-0.03045 to 0.06242	No	ns	0,742

Dunnett's multiple comparisons test results comparing margins of stability values for each recovery step to baseline. Base: Baseline of the eleventh to second last step before each perturbation. Pre: The final step before each perturbation. Post1–8: The recovery steps following each perturbation.

Table S3.3 Pairwise comparisons perturbation 1 – Sidák's multiple comparisons test.

Šídák's multiple comparisons test	Mean Diff.	95.00% CI of diff.	Below threshold?	Summary	Adjusted P Value
No Falls - Fall					
Base	0,004024	-0.01440 to 0.02245	No	ns	0,9988
Pre	0,005052	-0.02051 to 0.03062	No	ns	0,9995
Post1	0,007605	-0.09598 to 0.1112	No	ns	>0.9999
Post2	-0,02279	-0.1535 to 0.1079	No	ns	0,9997
Post3	-0,02411	-0.1034 to 0.05522	No	ns	0,9847
Post4	-0,009817	-0.09075 to 0.07112	No	ns	>0.9999
Post5	-0,01185	-0.08490 to 0.06121	No	ns	>0.9999
Post6	-0,02871	-0.08256 to 0.02514	No	ns	0,6685
Post7	-0,008071	-0.06118 to 0.04503	No	ns	>0.9999
Post8	-0,009311	-0.07055 to 0.05193	No	ns	>0.9999

Sídák's multiple comparisons test results comparing margins of stability values for each step between groups. Base: Baseline of the eleventh to second last step before each perturbation. Pre: The final step before each perturbation. Post1–8: The recovery steps following each perturbation.

Table S3.4 Pairwise comparisons perturbation 2 – Dunnett's multiple comparisons test.

Dunnett's multiple comparisons test	Mean Diff.	95.00% CI of diff.	Below threshold?	Summary	Adjusted P Value
No-Falls group					
Base vs. Pre	0,008318	-0.01515 to 0.03179	No	ns	0,8281
Base vs. Post1	-0,01473	-0.06648 to 0.03702	No	ns	0,9308
Base vs. Post2	0,08981	0.03304 to 0.1466	Yes	**	0,0025
Base vs. Post3	0,07654	0.02158 to 0.1315	Yes	**	0,0064
Base vs. Post4	0,09787	0.03970 to 0.1560	Yes	**	0,0015
Base vs. Post5	0,02964	-0.01919 to 0.07846	No	ns	0,3509
Base vs. Post6	0,0501	0.01970 to 0.08049	Yes	**	0,0018
Base vs. Post7	0,02855	-0.005532 to 0.06262	No	ns	0,1164
Base vs. Post8	0,02182	0.002659 to 0.04097	Yes	*	0,024
Falls group					
Base vs. Pre	0,003261	-0.02460 to 0.03113	No	ns	0,9994
Base vs. Post1	-0,02944	-0.1712 to 0.1124	No	ns	0,9728
Base vs. Post2	-0,0275	-0.08781 to 0.03281	No	ns	0,5454
Base vs. Post3	-0,02941	-0.1048 to 0.04599	No	ns	0,6815
Base vs. Post4	0,07376	0.01011 to 0.1374	Yes	*	0,025
Base vs. Post5	0,05788	0.01061 to 0.1052	Yes	*	0,019
Base vs. Post6	0,05733	-0.004099 to 0.1188	No	ns	0,0675
Base vs. Post7	0,02746	-0.01118 to 0.06610	No	ns	0,1862
Base vs. Post8	0,008855	-0.02093 to 0.03864	No	ns	0,8637

Dunnett's multiple comparisons test results comparing margins of stability values for each recovery step to baseline. Base: Baseline of the eleventh to second last step before each perturbation. Pre: The final step before each perturbation. Post1–8: The recovery steps following each perturbation.

Table S3.5 Pairwise comparisons perturbation 2 – Sidák's multiple comparisons test.

Šídák's multiple comparisons test	Mean Diff.	95.00% CI of diff.	Below threshold?	Summary	Adjusted P Value
No Falls - Fall					
Base	0,008126	-0.01263 to 0.02888	No	ns	0,9188
Pre	0,00307	-0.02759 to 0.03373	No	ns	>0.9999
Post1	-0,006585	-0.1528 to 0.1396	No	ns	>0.9999
Post2	-0,1092	-0.1847 to -0.03368	Yes	**	0,0022
Post3	-0,09783	-0.1964 to 0.0007808	No	ns	0,0527
Post4	-0,01598	-0.09367 to 0.06171	No	ns	0,9993
Post5	0,03637	-0.02620 to 0.09894	No	ns	0,5656
Post6	0,01536	-0.05527 to 0.08599	No	ns	0,9984
Post7	0,007041	-0.04695 to 0.06103	No	ns	>0.9999
Post8	-0,004834	-0.03689 to 0.02723	No	ns	>0.9999

Sídák's multiple comparisons test results comparing margins of stability values for each step between groups. Base: Baseline of the eleventh to second last step before each perturbation. Pre: The final step before each perturbation. Post1–8: The recovery steps following each perturbation.

Table S3.6 Pairwise comparisons perturbation 9 – Dunnett's multiple comparisons test.

Dunnett's multiple comparisons test	Mean Diff.	95.00% CI of diff.	Below threshold?	Summary	Adjusted P Value
No-Falls group					
Base vs. Pre	0,004193	-0.01607 to 0.02445	No	ns	0,9881
Base vs. Post1	0,1131	0.06616 to 0.1601	Yes	****	<0.0001
Base vs. Post2	0,06857	0.03058 to 0.1066	Yes	***	0,0009
Base vs. Post3	0,0816	0.04100 to 0.1222	Yes	***	0,0003
Base vs. Post4	0,05125	-0.004975 to 0.1075	No	ns	0,0795
Base vs. Post5	0,01562	-0.02261 to 0.05385	No	ns	0,7243
Base vs. Post6	0,01507	-0.01422 to 0.04436	No	ns	0,511
Base vs. Post7	0,003899	-0.01475 to 0.02254	No	ns	0,9872
Base vs. Post8	0,00558	-0.01534 to 0.02650	No	ns	0,9494
Fall group					
Base vs. Pre	-0,004054	-0.02354 to 0.01544	No	ns	0,9726
Base vs. Post1	0,0429	-0.06649 to 0.1523	No	ns	0,6771
Base vs. Post2	0,01765	-0.06933 to 0.1046	No	ns	0,976
Base vs. Post3	0,01082	-0.04576 to 0.06740	No	ns	0,9827
Base vs. Post4	0,029	0.001250 to 0.05674	Yes	*	0,041
Base vs. Post5	0,03807	-0.01819 to 0.09432	No	ns	0,2172
Base vs. Post6	0,02323	-0.02648 to 0.07294	No	ns	0,5229
Base vs. Post7	0,004075	-0.01613 to 0.02428	No	ns	0,9767
Base vs. Post8	0,01008	-0.01572 to 0.03587	No	ns	0,6803

Dunnett's multiple comparisons test results comparing margins of stability values for each recovery step to baseline. Base: Baseline of the eleventh to second last step before each perturbation. Pre: The final step before each perturbation. Post1–8: The recovery steps following each perturbation.

Table S3.7 Pairwise comparisons perturbation 9 – Sidák's multiple comparisons test.

Šídák's multiple comparisons test	Mean Diff.	95.00% CI of diff.	Below threshold?	Summary	Adjusted P Value
No Falls - Fall					
Base	0,003505	-0.02103 to 0.02804	No	ns	>0.9999
Pre	-0,004742	-0.03304 to 0.02356	No	ns	0,9999
Post1	-0,06674	-0.1935 to 0.06004	No	ns	0,5978
Post2	-0,04741	-0.1484 to 0.05354	No	ns	0,7232
Post3	-0,06728	-0.1370 to 0.002467	No	ns	0,0632
Post4	-0,01874	-0.07525 to 0.03776	No	ns	0,9701
Post5	0,02595	-0.03799 to 0.08989	No	ns	0,9054
Post6	0,01167	-0.04142 to 0.06476	No	ns	0,9986
Post7	0,003681	-0.02959 to 0.03695	No	ns	>0.9999
Post8	0,008001	-0.03747 to 0.05347	No	ns	0,9996

Sídák's multiple comparisons test results comparing margins of stability values for each step between groups. Base: Baseline of the eleventh to second last step before each perturbation. Pre: The final step before each perturbation. Post1–8: The recovery steps following each perturbation.

4

Perturbation-based balance training to improve balance control and reduce falls in older adults – study protocol for a randomized controlled trial

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Abstract

Background

Falls are a common cause of injuries and hospitalization among older adults. While conventional balance training appears effective in preventing falls, a relatively large number of training sessions are needed and retention of the effects after the training period is hard to accomplish. This may be because these interventions are not sufficiently task-specific for the mechanism of falls. Many falls in older adults occur due to unexpected external perturbations during gait, such as trips. Therefore, there is increasing interest in perturbation-based balance training (PBT), which is a more task-specific intervention to improve reactive balance control after unexpected perturbations. The literature suggests that PBT may be more effective and require fewer training sessions to reduce falls incidence in older adults, than conventional balance training. We aim to evaluate the effect of a three-session PBT protocol on balance control, daily life falls and fear of falling. Secondly, we will evaluate the acceptability of the PBT protocol.

Methods

This is a mixed-methods study combining a single-blind (outcome assessor) randomized controlled trial (RCT) using a parallel-group design, and qualitative research evaluating the acceptability of the intervention. The study sample consists of community-dwelling older adults aged 65 years and older who have recently fallen and visited the MUMC+ outpatient clinic. Subjects are randomized into two groups. The control group (n=40) receives usual care, meaning referral to a physical therapist. The intervention group (n=40) receives usual care plus three 30-minute sessions of PBT in the Computer Assisted Rehabilitation Environment. Subjects' balance control (Mini-BESTest) and fear of falling (FES-I) will be assessed at baseline, and 4 weeks and 3 months post-baseline. Daily life falls will be recorded with falls calendars until 6 months after the first follow-up measurement, long-term injurious falls will be recorded at 2-years' follow-up via the electronic patient record. Acceptability of the PBT protocol will be evaluated with semi-structured interviews in a subsample from the intervention group.

Discussion

This study will contribute to the evidence for the effectiveness of PBT using a training protocol based on the available literature, and also give much needed insights into the acceptability of PBT for older adults.

Background

Falls are a common cause of injuries and hospitalization among older adults.[1] Each year, one in three adults aged 65 years or older, and one in two adults above the age of 80 years, experience a fall.[2] In the Netherlands, around 108,000 older adults (332 per 10,000) visited the emergency department in 2018 after a fall incident, and 33% of them were subsequently admitted to hospital.[3] Falls are putting increasing demands on healthcare resources, with fall-related medical costs in the Netherlands of about 960 million euros in 2018.[3] If the incidence of falls remains unchanged, and with the aging of the population expected to increase, the number of falls in adults aged 65 years and older will have increased by 47% by 2050.[3] Falls often have serious physical consequences, such as fractures or head injuries.[4] In addition, there are psychological consequences of falling, which can have a strong negative impact on quality of life.[5] Up to 73% of older adults who have experienced a fall are afraid of falling again, which in turn can lead to decreased physical and social mobility.[6] Once an older adult has experienced a fall incident, their risk of sustaining future falls is greatly increased (OR 2.8 for all fallers, and 3.5 for recurrent fallers).[5,7]

A modifiable risk factor that has repeatedly been identified in the literature is the presence of gait or balance problems.[2,5,8] Many studies have shown that balance training can effectively reduce falls incidence in older adults, with or without specific disorders, by approximately 24%.[9-14] However, the optimal type, duration and frequency of balance training to reduce falls are not yet clear. Berg *et al*. described three aspects of balance, which should be functionally adequate to accomplish functional balance.[15] The first is the ability to maintain various postures, also referred to as static balance control. The second, is the ability to make postural responses to voluntary changes of body position, using mostly proactive balance control. The third is the ability to react to unexpected external disturbances (perturbations) of balance, also called reactive balance control.[15]

Conventional balance training has mostly focused on the first two aspects of balance, where proactive mechanisms of balance control are the most important.[16] While conventional balance training interventions appear effective in preventing falls, a relatively large number of training sessions are needed and retention of the effects after the training period is hard to accomplish.[17-19] This may be because many falls in older adults occur as a result of an unexpected external perturbation during gait, such as a slip or a trip.[20,21] The unexpected nature of such external perturbations forces individuals to rely mostly on reactive balance control. Since balance training seems highly task-specific, it is not likely that training proactive balance control will also improve reactive balance control, in view of the additional speed and stability requirements of these balance reactions.[22]

During the process of physiological aging, changes in the body lead to less efficient reactive balance control strategies, such as delayed onset of muscle responses, decreased magnitude of postural responses, and an increased level of co-activation in muscles.[23-25] Even in community-dwelling older adults who walk independently, there may be a substantial decline in reactive balance control, but this will not become evident until a slip or a trip occurs.[26] Despite this decline, the potential to adapt and improve reactive balance control through training seems to be retained with age[27], leading to an increasing interest in perturbation-based balance training (PBT).[28]

PBT is a form of training that aims to improve reactive balance control after unexpected external perturbations. In a safe and controlled environment, participants are repeatedly exposed to destabilizing perturbations during various activities of daily living. Many different training setups can be utilized, from fairly simple lean-and-release perturbations requiring only a safety harness, to advanced systems that can provide a wide variety of perturbation types and intensities during various tasks.

Studies of PBT have shown significant reductions in falls in older adults with and without specific disorders such as Parkinson's disease or stroke (with a relative risk of falls of 0.71 [95% CI 0.52 to 0.96] compared to various control groups).[29-36] Adaptation may occur faster with this type of training than with conventional balance training, offering the potential of achieving equal or better results with fewer training sessions.[34] For example, a study by Pai *et al*. showed a 50% reduction in the incidence of daily-life falls during twelve months of follow-up after only a single training session.[34]

In an earlier review, we included eight studies on PBT in older adults.[28] We concluded that PBT appears to be a feasible approach to falls prevention in clinical practice, and that a combination of types and directions of perturbation might offer the greatest benefits. Frequency and volume of training varies greatly between studies, and while there are studies showing positive effects with relatively low training doses, the optimal training characteristics are not yet clear. In this study protocol, we describe a PBT protocol including multiple types and directions of perturbations, with a training dose that we hypothesize to be suitable based on the current evidence.[28]

Besides improving balance and reducing falls incidence, PBT can significantly reduce the fear of falling.[37] Fear of falling can have a major impact on older adults. While it may initially be a reasonable response to experiencing a fall, and may lead to more cautious behavior, it can also have debilitating consequences when it leads to activity restriction.[6] If this occurs, fear of falling can lead to physical deconditioning and frailty, which can set off a negative spiral by increasing the risk of recurrent falls.[38]

While the body of evidence for the effectiveness of PBT for falls prevention is growing, there are other factors to consider.[8,32,34-36,39-41] The perturbations applied in these studies are of such a magnitude that they may not be acceptable to all older adults. Even the most effective interventions are likely to fail if they are not acceptable to the target population. Therefore, the literature recommends combining quantitative and qualitative methods to assess both the effectiveness and acceptability of a new intervention.[42] In this study, we will assess the acceptability of our training protocol through semi-structured interviews, utilizing the definition and theoretical framework of acceptability (TFA) described by Sekhon *et al*.[43]

This study protocol describes a mixed-methods study combining an outcome-assessor blinded randomized controlled trial (RCT), using two parallel groups (1:1) and a superiority design, with qualitative research concerning the acceptability of the intervention. The primary aim is to determine the effect of our three-session PBT intervention on balance control measured with the Mini-BESTest in community-dwelling older adults (≥65 years) who visit the outpatient clinic after a fall, in comparison to usual care. Secondly, we aim to determine the effect on real-life falls incidence during a six months follow-up period. We will also evaluate the effect on fear of falling measured with the Falls Efficacy Scale International (FES-I). A long-term follow-up evaluation will take place at 2 years post-baseline when each subjects' electronic patient record (EPR) will be checked with the aim of investigating the long-term effect of PBT on injurious falls.

Lastly, we aim to determine the acceptability of our three-session PBT protocol through semi-structured qualitative interviews in a sub-group of the intervention group in this study.

Methods

Study design

This is a mixed-methods study combining a single-blind (outcome assessor) randomized controlled trial (RCT) in a parallel-group design, with qualitative research to assess the acceptability of the intervention. This protocol was written in accordance with the Standard Protocol Items: Recommendations for Interventional Trials (SPIRIT) checklist. The study will be conducted at MUMC+ in Maastricht, the Netherlands from March 2019 until July 2021. The study was approved by the Medical Ethics Committee azM/UM (METC18-049).

Subjects

Community-dwelling older adults (65+) who have experienced a fall in the past three months and visit the MUMC+ outpatient clinic will be approached to participate in this study. To ensure that our sample includes only older adults at increased risk for falling, persons who fell during exercise activities (i.e. cycling) or due to actions of a third party, will be excluded. Similarly, persons using medication that is known to increase the fall risk will be excluded from this study. For a full description of the eligibility criteria, see **Table 4.1**.

Table 4.1 Full eligibility criteria.

Inclusion criteria	Exclusion criteria
Age ≥65 years	Diagnosed with osteoporosis
Community-dwelling	Recent fracture or severe contusion of the lower extremities, back or shoulders (in consultation with medical doctor)
Able to walk without a walking aid for ≥15 minutes	Any disease or disorder that may influence the safety of training (e.g. severe cardiopulmonary disease)
Recently having experienced a fall (≤3 months ago)	Falls caused by actions of third parties or during exercise activities
Having visited the MUMC+ outpatient clinic after their fall incident	Uncorrected vision problems
	Falls due to syncope
	Use of medication known to increase fall risk (antidepressants, benzodiazepines, sedatives, hypnotics, antipsychotics) (44)
	Use of painkillers that can decrease responsiveness (e.g. morphine, oxycodone) (44)
	Inability to provide written informed consent and communicate in Dutch
	Inability to follow instructions due to cognitive problems

Recruitment, randomization, blinding and treatment allocation

Eligible patients will be informed about this study by their medical doctor when they visit the outpatient clinic of the MUMC+. If patients are interested in the study, they will receive written information and will be asked for their permission to be phoned by the investigators. Patients are given the opportunity to read the study information at home and will be phoned by the investigators 3 to 7 days later. If a patient wants to participate, an appointment will be scheduled to visit the MUMC+ department of physical therapy. During this visit, any remaining questions will be answered and written informed consent will be obtained.

After this, the investigator will check the eligibility criteria. If the subject meets the criteria, baseline measurements will be performed. When these have been completed, the subjects will be randomized to the intervention- or control group. This will be done using a 1:1 ratio stratified block randomization (block sizes 2 and 4 will be randomized). Randomization will be stratified based on sex (male versus female) and number of falls during the past year (1 versus 2 or more). This stratification will result in four different strata. The randomization sequence will be generated using an online random number generator. The allocation will be concealed by using sequentially numbered, sealed opaque envelopes. The person preparing the allocation concealment mechanism will be a different person than the one enrolling the subjects and assigning them to a group. The allocation sequence list will be kept in a locked drawer, which can be accessed only by the principal investigator.

Timeline

The first study visit for subjects consists of two parts; t_{-1} is where subjects make their final decision on participating in the study, informed consent is obtained and the eligibility criteria are checked. If a subject meets all eligibility criteria, this visit is combined with t_0. At t_0, baseline measurements are performed by the outcome assessor, which will be blinded to treatment allocation. Subjects are explicitly instructed to hide their treatment allocation from this researcher. If the treatment allocation of an individual subject is revealed to the outcome assessor, a second blinded outcome assessor will take over the remaining measurements. After baseline measurements, the subject is randomized to the control- or intervention group by the same researcher that enrolled the subject in the study. For subjects in the intervention group, this visit is followed by three training sessions in 3 weeks. Both groups have their t_1 visit at 4 weeks post-baseline, and a t_2 visit 3 months after that, t_2 being the last study visit for subjects. From t_0 on, all subjects will fill in falls calendars until 6 months after t_1. A final check of the EPR at t_3, 2 years post baseline, concludes data collection for this study. An overview of the study timeline is presented in **Table 4.4**.

Interventions

Subjects in this study will be randomized to the control group (usual care) or the intervention group (usual care + PBT). Training in the intervention group will be provided by specifically trained physical therapists in association with clinical operators of the CAREN system.

Control intervention (usual care)

All included subjects will receive usual care. Usual care in the MUMC+ outpatient clinic consists of a referral for physical therapy treatment for the injuries sustained during the fall incident, if the medical doctor determines that this is indicated (for example, mobility and strength exercises after a shoulder fracture). During the study, the outcome assessor will monitor whether each subject has used their referral to visit a physical therapist, how many times, and what components (i.e. strength training, mobility exercises, balance exercises) were included in the physical therapy treatment.

Experimental intervention

The experimental intervention in this study is PBT. The aim of this training program is to improve reactive balance control in older adults by practicing balance recovery from unexpected perturbations in a safe and controlled environment.

Training setup

Training will take place on the CAREN system at the MUMC+ department of physical therapy. The CAREN is a dual-belt treadmill system embedded in a motion platform with 6 degrees of freedom and surrounded by a 180 degree screen. The treadmill and the motion platform can both provide reactive balance challenges separately or combined, providing a wide array of possible types and directions of perturbation. Virtual reality environments are projected onto the screen to make the training activities more immersive. Subjects will wear a safety harness at all times during training to protect them from injuries in case of an unsuccessful balance recovery.

Training dose

Based on previous studies, we hypothesize that three training sessions of 30 minutes each will be enough to facilitate adaptation of reactive balance control.[32,34-36,39-41]

Perturbation intensity and progression

While it is not clear exactly how perturbation magnitude impacts motor learning and retention, it appears that high-magnitude perturbations (where the subject initially needs the safety harness to recover their balance) result in fast and significant adaptation with long-term skill retention.[28] However, with regard to the safety and acceptability of training, a more progressive and personalized approach that is still challenging seems more reasonable. We therefore decided to monitor how challenging the training is for each subject, and to individualize the progression of difficulty levels. With this goal in mind, we will use a numeric rating scale (NRS) where each subject will rate the difficulty of maintaining balance control during training on a scale from 1 to 10. The following guideline will be used to interpret how challenging the training is for each subject; NRS 1-3 barely challenging, NRS 4-5 mildly challenging, NRS 6-7 challenging, NRS 8-9 very challenging, NRS 10 unsuccessful balance recovery. The NRS scale will be monitored regularly during training, with the aim to train at an NRS of 6 to 9. If a subject scores the level of challenge as below 6 and this score is consistent with the subjective impression of the physical therapist, the perturbation difficulty level will be increased. The maximum perturbation difficulty levels displayed in **Tables 4.2** and **4.3** are based on the possibilities of the CAREN system, and on pilot testing with healthy older adults.

Perturbation types

From the available literature, we concluded that incorporating multiple perturbation types and directions might be of most benefit.[28] Each training session will therefore incorporate platform (translations and tilts in the forward, backward, left and right direction) and treadmill perturbations (unilateral treadmill belt accelerations and decelerations) during standing and walking. Each perturbation type has seven increasing difficulty levels (**Tables 4.3a-c**). For each subject, the first training session will be started with perturbations of each type on level 1. Difficulty levels will then be increased based on individual training progression and NRS scores.

Training procedures

The first training session on the CAREN system will start with a period of familiarization, where the subject can get used to the system by walking on the treadmill. Subjects will report an NRS score for how comfortable they feel walking on the CAREN before and during familiarization (0; very uncomfortable to 10; fully comfortable). If a score of 7 or higher is reached, familiarization is complete. We expect that this will occur within 6-7 minutes.[45]

After this, each subjects' comfortable walking speed will be determined using a ramped protocol; the walking speed will start at 0.5 m/s and will gradually be increased until the subject says 'stop' when they think their comfortable walking speed is reached. The subject will walk at this speed for approximately one minute to check if any adjustments need to be made.

The consecutive sessions will start with a warming-up during which the subject will walk on the treadmill for approximately 3 minutes on a level surface and readjust to the system. Each training session will consist of three parts: gait adaptability, static reactive balance, and dynamic reactive balance. Training difficulty can be progressed by increasing the perturbation magnitude and walking speed. During the second and final training sessions, cognitive and motor dual tasks can also be added to increase training difficulty. Training adherence will be monitored throughout the study, and subjects will be encouraged to reschedule any missed training sessions.

Gait adaptability

Subjects will walk in a virtual environment on a path through a forest, with various slopes and turns. Both the incline/decline of the slopes and the sharpness of the turns will have a standardized starting level of 20% (out of 100%), which will then be progressed in steps of 5% to 15%. A difficulty level of 20% corresponds to a maximum incline/decline and rotation of 2 degrees. Each 5% increase in difficulty level means an increase in the maximum incline, decline and rotation of 0.5 degrees. For the percentage by which the difficulty level will be increased for each NRS score, see **Table 4.2**.

Table 4.2 Perceived difficulty scores, according to the NRS score and their corresponding increase in difficulty level.

NRS score (0-10)	Increase in difficulty level (percentage)
1	15%
2	15%
3	15%
4	10%
5	10%
6	5%
7	5%
8	0%
9	0%
10	0% or decrease by 5-10%

NRS score: Numeric Rating Scale score. Increase in difficulty level: The percentage by which the difficulty level will be increased if the subject scores the corresponding NRS score.

Static reactive balance

Subjects will stand on the CAREN while the platform and treadmill make sudden movements. The platform can shift or tilt to anterior, posterior, left and right. The treadmill belt can unilaterally accelerate from standstill. All possible perturbations have seven difficulty levels (see **Table 4.3a-c**). Training will start at level 1 for each subject.

Dynamic reactive balance

Subjects will walk on the treadmill at their comfortable walking speed, while the above mentioned platform and treadmill perturbations are applied. The treadmill perturbations will consist of unilaterally accelerating or decelerating the treadmill belt for short periods of time, simulating a trip or a slip, respectively (**Table 4.3c**).

Table 4.3a Difficulty levels and their corresponding perturbations of platform displacement and maximum speed of shift.

Difficulty level	Displacement (cm)	Maximum speed (m/s)
1	5	0.11
2	7.5	0.16
3	10	0.21
4	12.5	0.26
5	15	0.31
6	17.5	0.36
7	20	0.41

Displacement: The distance in centimeters which the platform will move during a perturbation of a certain level. Maximum speed: The maximum speed at which the corresponding platform displacement will be reached.

Table 4.3b Difficulty levels and their corresponding perturbations of platform angles and maximum speed of the platform tilt.

Difficulty level	Tilt left/right (degrees)	Tilt forward/backward (degrees)	Speed (degrees/s)
1	3	2	6.2
2	4.5	3.5	9.2
3	6	5	12.2
4	7.5	6.5	15.2
5	9	8	18.2
6	10.5	9.5	21.2
7	12	11	24.2

Tilt: The number of degrees by which the platform will tilt to a certain side during a perturbation of the corresponding level. Speed: The maximum speed at which the corresponding platform tilt will be reached.

Table 4.3c Difficulty levels and their corresponding perturbations of treadmill belt acceleration/deceleration, speed (increase) and duration of unilateral treadmill acceleration and deceleration.

Difficulty level	Acceleration/Deceleration (m/s^2)	Speed (increase/decrease, m/s)	Duration (s)
1	3	0.5	0.20
2	3	0.85	0.28
3	3	1.2	0.36
4	3	1.55	0.44
5	3	1.9	0.52
6	3	2.25	0.60
7	3	2.5	0.68

Speed: The increase or decrease in unilateral treadmill belt speed in m/s for each difficulty level. Duration: The amount of time during which the increased speed is maintained.

Outcomes

Balance control (main outcome)

The main outcome in this study is balance control, which will be measured with the Mini Balance Evaluation Systems Test (Mini-BESTest). The Mini-BESTest has been identified as the most comprehensive measurement tool to assess balance in community-dwelling older adults.[46] It measures balance in four categories: proactive balance, reactive balance, sensory orientation and dynamic gait. Each of the 14 tasks is scored on a three-point scale, with a total score that can range from 0 to 28 points. A higher score corresponds with better balance control. Proactive balance is tested using a sit-to-stand transfer where the subject has to try not to use their hands, standing on tiptoes, and standing on one leg. Reactive balance is tested with therapist-applied lean-and-release perturbations in the forward, backward and sideways directions. Sensory orientation is tested by standing with feet together, standing with feet together and eyes closed on a foam surface, and standing on a slope with eyes closed. Dynamic gait is tested with five tasks; suddenly changing gait speed, walking while turning the head left and right, walking and turning, stepping over an obstacle while walking, and Timed Up and Go performance. The Mini-BESTest has good psychometric properties.[47,48] Cut-off values indicating increased fall risk for the Mini-BESTest are age dependent; ≤25 points for people 60 to 69 year of age, ≤23 points for 70 to 79 years, ≤22 points for 80 to 89 years and ≤17 points for 90 years and older.[49] The minimal detectable change on the Mini-BESTest is 3.5 points and the minimal important change is 4 points.[50] Balance control will be measured at baseline, T_1 and T_2.

Retrospective falls incidence

At baseline, the number and circumstances of falls during the past year of each subject will be recorded. A fall is defined as 'an event which results in a person coming to rest inadvertently on the ground or floor or lower level'.[51] We will use an adapted version of the 'falls history questionnaire' as presented in the book *'Falls in older people: risk factors and strategies for prevention'.*[52] This questionnaire records if a fall has occurred in the previous period (12 months), where it has happened, what the perceived cause was, and if and what kind of injuries were sustained. The outcome assessor will fill in this questionnaire together with the subject to make sure that the recorded data is as comprehensive and clear as possible.

Prospective falls incidence

From the moment of inclusion, the prospective falls incidence of each subject will be monitored for up to 8 months (the potential training period + 6 months) post baseline. The prospective falls incidence will be monitored with falls diaries and questionnaires. The falls diary is a calendar that the subject will fill in at the end of each day. They are instructed to put an 'X' if they did not fall that day, or a number representing the number of times they fell during that day. At the end of each month, subjects will fill in the falls history questionnaire about that particular month, and send this back to the researchers in pre-addressed and pre-paid envelopes. If a fall incident is reported, the researcher will follow this up with a short phone call to elaborate on the circumstances and consequences of this fall. If a calendar has not been returned within 10 working days after the end of the month, the researcher will remind the subject with a phone call. A final follow-up will take place at 2 years post-baseline, where the researcher will check each patients' EPR, to see if there were any more hospital visits due to injurious falls.

Fear of falling

Fear of falling will be measured with the Falls Efficacy Scale International (FES-I, Dutch version). This version of the falls efficacy scale is a 16-item questionnaire developed to determine if a person has confidence in their ability to perform a range of daily activities without falling. It has been adapted to be more suited to older adults, including a range of activities from very basic to more complex.[53] The questionnaire will be filled in by the subject with the help of the outcome assessor. Sixteen items are scored on a four-point (1-4) scale, with a maximum score of 64 points. A higher score corresponds with a greater fear of falling. The Dutch version of the FES-I has good reliability and validity and discriminative power in older adults.[53-56] Fear of falling will be measured at baseline, T_1 and T_2.

Acceptability of the intervention

This study will evaluate not only the effect but also the acceptability of the intervention. In a sub-sample of the intervention group, semi-structured interviews will be conducted to investigate the acceptability of the PBT protocol. Each of these subjects will be interviewed once (for approximately 30 minutes) after completing the intervention. The interview guide will be based on the TFA, which consists of seven subsections:

- Affective attitude: how does the subject feel about the intervention, what is their opinion about it?
- Burden: did participating in the intervention take (a lot of) effort in terms of exertion or balance?
- Ethicality: did the intervention fit the subject's previous views on falls prevention?
- Intervention coherence: did the subject understand the goal(s) of the intervention and how it works?
- Opportunity costs: did the subject have to give up other opportunities to take part in the intervention (e.g. cancel other appointments)?

- Perceived effectiveness: did the subject notice any effects (physical or otherwise) of the intervention, during training or after their participation?
- Self-efficacy: how confident was the subject about their ability to participate in and complete the intervention?

Two interviewers will be present at each interview; one will lead the interview, while the other will observe non-verbal communication, make notes, and help keep track of the interview guide. In addition to the framework, any perceived barriers/facilitators to participating in the intervention will be discussed. The interviews will take place at MUMC+ and will be administered by the research staff who are familiar with the training protocol.

Table 4.4 Patient flow of enrolment, assessments and interventions.

	Enrollment	**Allocation**	**Post-allocation and enrollment**		
Timepoint	**t_{-1}**	**0**	**t_1**	**t_2**	**t_3**
Enrolment					
Eligibility screening	X				
Informed consent	X				
Allocation		X			
Interventions					
Usual care		◆—	—◆		
Usual care + PBT		◆—	—◆		
Assessments					
Demographic variables	X	X			
Retrospective falls questionnaire		X			
FES-I		X	X	X	
Mini-BESTest		X	X	X	
Falls calendars + questionnaires		◆—	—	—	—◆
Interview acceptability			X		
EPD check injurious falls					X

PBT Perturbation-based balance training, FES-I Falls Efficacy Scale International, Mini-BESTest Mini Balance Evaluation Systems Test.

Data management

Each subject will receive a unique identification code when they are included. All data will be collected and stored anonymously and linked to this code. Data will be collected on a paper case report form and paper questionnaires. The data will then be digitized by a trained research assistant and will be verified by the coordinating researcher before analysis. Trial conduct and a sample of the data will also be verified by an independent research monitor during and at the end of the study, and at two time-points during the study. Data from the semi-structured interviews will be recorded using a voice recorder and saved in a password-protected folder, while regular back-ups will be made to a password-protected external hard drive. The recordings will be deleted from the voice recorder immediately after they have been saved on the computer and external hard-drive.

Sample size

Sample size was calculated in G*power 3.1.9.2 and was based on the primary outcome of this study, difference between means on balance measured with the Mini-BESTest at T_1. The effect size *d* (0.61) was calculated based on values from an article with a similar study population and an intervention aimed at improving dynamic balance control.[57] We assumed that our control group would remain stable as they receive no extra training aimed at balance improvement. Sample size was based on a one-tailed independent samples t-test, an α of 0.05, power (1-β) of 0.80 and allocation ratio of 1. This results in a required sample size of *n*=72. Accounting for an expected loss to follow-up of 10%, the final sample size is *n*=80. Sample size was estimated conservatively, making no assumptions about the correlation between predictors (group allocation and baseline score) added into the model and the outcome variable.

For the purpose of investigating the acceptability of the PBT protocol, a sub-sample from the intervention group will be included. The sample size will be based on the concept of theoretical saturation as described by Glaser & Strauss.[58] If there are two consecutive interviews that provide no new information, no new interviews will be planned. We expect to include approximately 15 subjects for the interviews.

Statistical analysis

Data will be analyzed using the Statistical Package for the Social Sciences (SPSS) version 23.0 (SPSS, Chicago, Ill., USA). Descriptive statistics will be used to explore the data and will be presented in tables and figures. Data will be displayed as mean and standard deviation (SD) or as median and interquartile range (IQR), depending on normal distribution of the data. Categorical data will be summarized by frequency (n) or percentage (%). Data will be analyzed on an intention-to-treat basis; missing data will be imputed using multiple imputation. In all statistical analyses, statistical significance will be set at $P<0.05$. Data-analysis will be performed by a researcher who is blinded to the group allocation.

Primary analysis will test whether there is a significant difference in balance, as measured with the Mini-BESTest, between the control- and intervention groups at T_1. This will be analyzed using multiple linear regression. Based on the randomization, no between-group differences in variables are expected. However, if there are differences at baseline (based on qualitative appraisal of the baseline table), these factors will be entered into the model. The secondary study parameter 'fear of falling' will be analyzed using the same method. The incidence of falls will be analyzed using generalized linear regression with a link function appropriate for the number of falls, using the mean number of retrospective and prospective falls per person-time unit.

A longitudinal analysis will be performed as a secondary, more explorative analysis of balance (Mini-BESTest) and fear of falling (FES-I) over time. A linear mixed effect model will be used to assess the treatment effects, since this model uses all available data, accounts for missing data using a likelihood based method - where missingness at random (MAR) is assumed - and takes the correlation between repeated measurements within a subject into account. The fixed part of the model consists of time, time*treatment, and other covariates that are related to the outcome (power gain) and/or to the missingness (to ensure MAR). The treatment factor, indicating the different treatment groups, is not included, since no group effect is assumed at baseline due to randomization. As for the random part of the model, an unstructured covariance structure is assumed for the repeated measures.

For the analysis of the qualitative data, the interviews will be transcribed verbatim. All transcriptions will be double-checked by a second researcher. A summary of the interview will be sent to the subject, so they have the opportunity to check the information and provide feedback. A deductive content analysis based on the theoretical framework of acceptability will be performed on the data using NVivo software, version 12 (QRS International). The transcripts will be coded independently by two researchers. After this, any differences in coding will be discussed. A third researcher will be available to reach consensus if necessary. An unstructured categorization matrix will be utilized, so topics that do not fit the initial framework can be added based on inductive content analysis.[59] If new topics arise during data collection, they will be added to the interview guide.

Circumstances and consequences of fall incidents, whether injurious or not, will be reported qualitatively, and using descriptive statistics.

Adverse events

All adverse events until 2 weeks post T_1, and after that all spontaneously reported adverse events, will be recorded and reported in the final publication of this study.

Trial status

Enrolment for this study started on March 12, 2019. Recruitment for this study is currently ongoing, and is expected to be completed by December 31, 2020.

Discussion

Strengths

This study will assess the effects and acceptability of a PBT intervention compared to usual care in an outpatient setting. It is designed as a mixed-methods randomized controlled trial in which, not only the effectiveness, but also the acceptability of the intervention will be assessed, to facilitate further development and implementation in clinical practice of this potentially effective intervention. The training protocol for the intervention has been developed based on principles of training and a critical review of findings from the available literature. It is described in detail to improve reproducibility, interpretation and comparability of the study results. A virtual environment, while it may not yet be fully optimized, is utilized to ensure the realism of the training activities. The duration of the training sessions has been designed to fit within a regular physical therapy treatment session, to promote the potential for incorporating this type of training in the usual care process of patients in the future. While the sample in this study will be controlled by inclusion and exclusion criteria to ensure that an at-risk sample is included, we decided not to include subjects based on a specific disease or disorder, to promote the external validity of the results. A 6 months' follow-up of daily-life falls incidence and a 2-year follow-up of injurious falls have been included to measure the effect of this intervention on subjects' daily life and their long-term risk of sustaining recurrent injurious falls in addition to the balance measured in the lab.

Weaknesses

The main weakness of this study is that it is not powered for all included outcome measures. The power calculation was based on the main outcome, i.e. balance control measured with the mini-BESTest, while for older adults their real-life falls incidence may be more essential. However, powering the study for this outcome is not possible, as the required sample size would not be achievable due to practical (time, resources) constraints. Secondly, the choice to include a broad spectrum of perturbations in the training protocol is based on our conclusions from the literature. This may be the right approach to ensure that each subject is prepared for multiple types and directions of perturbation, but it may also have a negative effect because the training dose of each individual perturbation type is lower. The results of this study will indicate whether this was a good approach. Finally, a disadvantage of the intervention is that it is device-dependent and only individual training is possible. Even though efforts are made to improve the external validity of the study findings, the feasibility of applying this intervention in usual care will have to be investigated in future studies.

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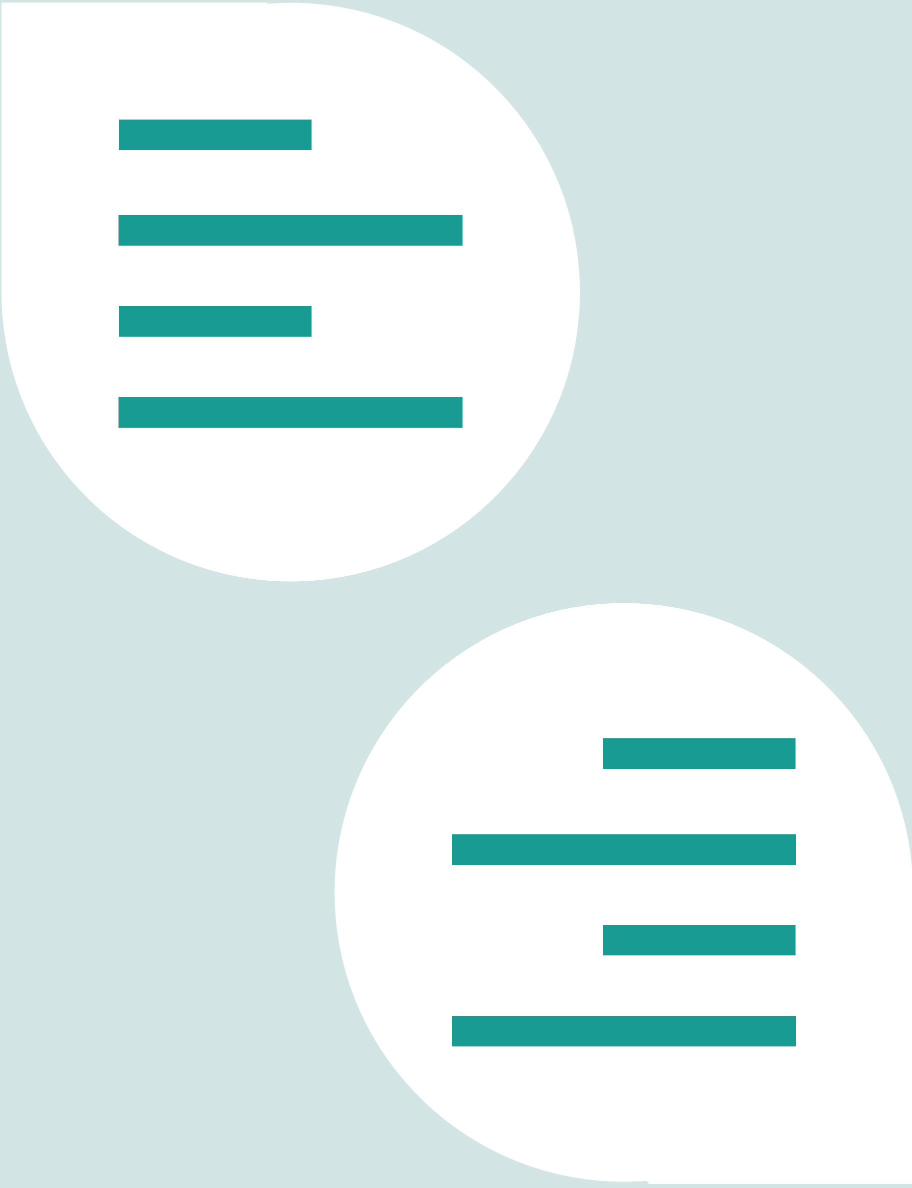

5

Acceptability of a perturbation-based balance training program for falls prevention in older adults: a qualitative study

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Abstract

Introduction

Perturbation-based balance training (PBT) is reported to effectively reduce falls in older adults, and may even be superior compared to various exercise programs. Due to the nature of the intervention, requiring unpredictable balance perturbations, the question arises whether acceptability is an issue in PBT.

Objective

To evaluate the acceptability of PBT in older adults with a recent history of falls.

Design, method, participants and setting

Qualitative study in which semi-structured interviews were conducted in 16 older adults (14 females and 2 males, mean age 73.6 ± 6.0 years) who completed a three-session PBT protocol as part of another study in a university medical centre in The Netherlands. Typical case and purposive sampling strategies were applied. Interviews were based on the theoretical framework of acceptability (TFA) alongside context-specific factors and analysed using a template analysis approach.

Results

The results indicate that this PBT protocol is perceived as acceptable by older adults with a recent history of falls, and highlight key areas for potential future modifications. Enjoyment of the novel training and technology, being able to feel safe during training and perceived impact of increased self-efficacy and balance confidence were identified as facilitating factors. Potential issues included initial apprehension or anxiety during training and perceived impact being predominantly psychological instead of physical. Complimentary to the TFA one additional theme emerged, which described challenges regarding the training setting such as preference for group training in some participants and travel to the training location.

Conclusions

The results suggest that PBT is perceived acceptable by older adults with a history of falls. Increasing the social aspect of training and sharing experiences of peers may be considered to enhance acceptability to new participants who initially feel apprehensive or anxious about their ability to participate in future implementation of PBT.

Introduction

Falls in community-dwelling older adults can be effectively reduced through exercise interventions including balance training.[1] However, the search for the optimal balance training program for falls prevention is still ongoing. With conventional balance training, a relatively high number of training sessions are needed, discontinuation rates are high and retention of training effects is hard to accomplish.[2,3] Moreover, conventional balance training seems not sufficiently task-specific to prevent falls due to slips or trips during walking, which cause up to 60% of falls in community-dwelling older adults.[4,5] It is not likely that conventional balance training, mostly targeting volitional movements, will improve the change-in-support reactions (e.g. taking a quick step) needed to prevent a slip or a trip, due to the additional speed and stability requirements of these balance reactions.[6] Therefore, an increasing interest has arisen in more task-specific balance training interventions, such as perturbation-based balance training (PBT).

PBT aims to improve rapid balance reactions after unexpected external perturbations. During PBT, participants are repeatedly exposed to destabilizing perturbations while performing activities of daily living in a safe and controlled environment. A systematic review by Mansfield *et al*. indicated that PBT may be more effective in reducing daily-life falls in older adults, compared to various interventions ranging from no exercise to individualized physical therapy (risk ratio 0.71, 95% CI=0.52 to 0.96; P=0.02).[7] With PBT, balance adaptation may occur faster, potentially achieving equal or better results with fewer training sessions compared to conventional balance training.[8]

However promising, even effective interventions are likely to fail if they are not acceptable to the target population. The more acceptable the intervention, the more likely that adherence will be high.[9] In turn, higher adherence (>80%) may result in larger effects.[10] Due to the nature of the intervention, the question arises whether acceptability is an issue in PBT. In 2019, Okubo *et al*. found in a pilot study of 10 healthy older adults that self-reported anxiety levels before a training session increased significantly with increasing unpredictability of PBT.[11] Unpredictable perturbations are required in PBT to maximize learning of reactive balance control, yet these perturbations may cause anxiety and consequentially decrease acceptability.

So far limited evidence exists about the acceptability of PBT. Previous studies reported high training adherence rates, and no significant differences in drop-out rates between PBT and control groups receiving exercise or flexibility training.[12-14] However, while quantitative data such as adherence rates may be indirect indicators of acceptability, the full-fledged concept of acceptability is a subjective evaluation made by individuals who experience an intervention.[9] In 2017, Sekhon *et al*., proposed the Theoretical

Framework of Acceptability (TFA) in which acceptability is viewed as a multifaceted construct, consisting of seven components.[9]

To our knowledge, no studies thus far have focused on qualitative aspects of acceptability of PBT in older adults. The aim of this study is to explore acceptability of PBT as perceived by older adults with a recent history of falls. Their views on the components constituting acceptability will be explored. The findings will enable optimisation of future implementation of PBT in clinical practice.

Methods

Study design

A qualitative study consisting of semi-structured interviews was conducted. All participants provided written informed consent. This study was approved by the Medical Ethics Committee of MUMC+ (Maastricht University Medical Center) and Maastricht University (METC NL67131.068.18). The study is reported in line with the COREQ statement.[15]

Context, study participants and sampling

Older adults who participated in PBT as part of a RCT were included.[16] Community-dwelling older adults (age ≥65 years) who visited the hospital's outpatient clinic due to a fall incident were informed about the study, and approached by telephone a 3-7 days later. Participants were included in the RCT if they were able to walk for 15 minutes without a walking aid. Exclusion criteria included any risk factors to them participating in PBT (e.g. diagnosed osteoporosis, severe cardiopulmonary disease), or inability to communicate in Dutch. Participants were eligible for the qualitative interviews after they had completed the PBT. They were selected by the PBT trainers through a combination of typical case and purposive sampling, to select those participants who were representative of the study population and were expected to provide the most detailed input.

The PBT protocol consisted of three 30-minute sessions, during which participants were exposed to sudden balance perturbations while they stood and walked on a dual-belt treadmill embedded in a moveable platform (Computer Assisted Rehabilitation Environment (CAREN), Motek Medical BV). During the training, virtual environments were projected on a 180^{o} screen in front of the platform. Each session consisted of three standardized conditions, while progression of difficulty levels in each condition was individualized.

1. Gait adaptability: participants walked on the treadmill while a virtual environment of a forest road, with various slopes and turns, was projected onto the screen. The platform moved correspondingly.

2. Static reactive balance: participants stood on the platform while the platform and treadmill made sudden, variable and unpredictable movements to perturb balance.

3. Dynamic reactive balance: this training condition was similar to the one above, only the perturbations were applied while the participant was walking on the treadmill.

A detailed description of the PBT protocol is published elsewhere.[16] For an impression of the PBT setting, see **Figure 5.1**.

Figure 5.1 Picture of a participant during PBT. Picture published with participant's permission.

Theoretical framework

The interviews were based on the TFA as proposed by Sekhon *et al*.[9] In this framework, acceptability is defined as a multi-faceted, seven component construct, including: affective attitude, burden, ethicality, intervention coherence, opportunity costs, perceived effectiveness and self-efficacy. **Table 5.1** provides an overview of our operationalisation of each construct and an example of a related question from our interview guide (**Supplemental File 5.1**). Questions regarding context-specific barriers and facilitators (e.g. training location, supervision during training) to participate in PBT were added to gain insight in their influence on PBT acceptability.

Table 5.1 Theoretical framework of acceptability themes and interpretation.

Theme	Interpretation
Affective attitude	How an individual feels about the PBT *How do you feel about the training? What made you feel this way?*
Self-efficacy	The participant's confidence in their ability to perform the PBT *How did you do in the training?*
Perceived effectiveness	The extent to which the participant perceives the PBT to potentially and actually (observed) be effective *To what extent did you experience effects from the training?*
Ethicality	The extent to which the intervention had good fit with an individual's value system and expectations of a falls prevention intervention *To what extent did the training fit with your views on falls prevention?*
Intervention coherence	The extent to which the participant understands the aim of PBT and how it works *In your own words, what was the aim of the training?*
Burden	The perceived amount of effort that was required to participate in the PBT *To what extent did you find the training strenuous? To what extent did you find the training challenging?*
Opportunity costs	The extent to which benefits, profits or values were given up to participate in the PBT *To what extent did you forego other opportunities to participate in the training?*

PBT; perturbation-based balance training

Interview procedure

The interviews took place at the hospital, within one to three weeks after training completion, between February 2020 and May 2021. Interviews and analysis were completed before results on the effectiveness of the PBT protocol were analysed. The first 13 interviews (of in total 16) were led by a researcher (MG) who was involved in the PBT program, because she was familiar with the specifics of the training and could ask targeted follow-up questions. A second researcher was always present at the interviews as an observer, to help keep track of the interview guide, and take field notes. A verbal summary was given at the end of each interview and a written summary was sent to each participant for a member check. Interviews were conducted iteratively; the interview guide was adjusted after the first 3 interviews to include emerging themes. This process was repeated after 10 and 13 interviews were completed. All interviews were recorded using a digital voicerecorder and transcribed verbatim. Any names and other possible identification information were removed from the transcripts. As the interviews and transcripts were in Dutch, all quotes presented were translated with care to conserve the original meaning.

Analysis

Interview transcripts were analysed using a template analysis approach.[17,18] The a priori template was formed based on the TFA and interview guide. Two researchers (MG and JS) independently coded the first three interviews, using NVivo 12.[19] After coding, they discussed the codes until consensus and formed an initial template. This process was repeated for the next three interviews. Consensus was then reached that this third template version covered the transcripts that were analysed so far. MG subsequently coded the remaining interviews using the third template version. MG and JS discussed if any changes needed to be made to the template based on the later interviews. After the 9th interview was coded, no more changes to the template were indicated. This was confirmed by coding the remaining 4 interviews, and coding saturation was reached.[20]

Reflexivity and triangulation

As MG was involved in the PBT for these participants, as well as sampling and interviewing, it was possible that there was researcher bias or that participants were more inclined to give desirable answers. For the purpose of interviewer triangulation, three additional interviews (interviews 14-16) were conducted by an independent researcher (AW) to confirm or reject previous responses. Coding of these three interviews revealed no new codes, which can be interpreted as secondary confirmation of the coding template and saturation. Participants did not give different answers to different interviewers. JS and AW were not involved in the RCT on PBT and represented an outsider perspective in the design and review of the interview guide, coding and analysis, therewith contributing to further researcher triangulation. Through comparison and discussion of the transcripts, the authors then reached consensus on the most important themes from the interviews.

Patient and public involvement

Patients were first involved in pilot testing of the PBT protocol in this research, and the training protocol was fine-tuned based on their feedback. The aim of this study is to explore participant’s perceptions and views on the acceptability of the training, which may be used to guide design or implementation of future PBT interventions.

Results

Participant description

Sixteen participants (14 females and 2 males, mean age 73.6 ± 6.0 years) were approached, all of which accepted. For comparison, the RCT included a total of

82 participants, of which 39 were randomized to the PBT group (median age 73 years (IQR 10 years), 31 females and 8 males). **Table 5.2** provides an overview of participants and characteristics. Nine interviews were conducted at the hospital, seven were telephone interviews due to restrictions related to the COVID-19 pandemic. Interviews lasted 15-35 minutes. One participant (P031) missed one training session due to COVID-19 restrictions. Training adherance was 93,7% for the full PBT group, and 98,3% for participants included in this qualitative study.

Table 5.2 Overview of participant and interview characteristics.

Participant	Sex (F/M)	Age (years)	Falls previous year (n)	Interview type	Interviewer
P022	F	79	1	Face-to-face	MG
P023	F	80	1	Face-to-face	MG
P026	M	65	1	Telephone	MG
P027	F	76	2	Face-to-face	MG
P030	F	83	1	Telephone	MG
P031	M	67	1	Telephone	MG
P032	F	79	1	Telephone	MG
P040	F	73	2	Face-to-face	MG
P042	F	65	2	Face-to-face	MG
P043	F	74	1	Face-to-face	MG
P044	F	79	4	Face-to-face	MG
P045	F	74	1	Face-to-face	MG
P050	F	79	1	Face-to-face	MG
P068	F	70	1	Telephone	AW
P069	F	66	3	Telephone	AW
P082	F	69	1	Telephone	AW

F = female, M = male.

Perceptions of acceptability

The findings are presented below for each of the TFA components, along with illustrative quotes from participants. The theme ‘training setting’ was added, this theme includes context-specific barriers and facilitators that were described by the participants.

Affective attitude

Overall, participants described that they felt the PBT was an enjoyable experience. Most participants positively related this to the novelty of the experience, reporting feelings of curiosity and excitement. In contrast, some participants related this novelty to a feeling of suspense, and sometimes feeling unsure about their ability to participate in PBT at the start of the first training session. Most often this was described as a good amount of suspense and curiosity about what would happen, and not perceived as a barrier.

> P044 *''I didn't know what I could expect. But I said: Guys, I'll just see what happens, I'll leave it up to you. (…) In the beginning, you don't know what is going to happen to you. You feel a little insecure. But I was glad that I did it.''*

One participant described feeling anxious during the first training session, a feeling that fortunately decreased throughout the following sessions.

> P030 *''Now you know what you have to do so it's different. But at first it's kind of a startle response I think.''*

All participants reported that feeling safe and able to challenge themselves without fear of falling was closely related to a positive experience. The safety equipment (especially the safety harness), feeling heard by the trainer and receiving information during the training session were identified as important facilitators.

> P050 *''And again, (laughing) I was very happy that I didn't need to hang from those ropes* [safety harness]*, but I had complete faith that if anything were to happen I definitely would not fall. So that didn't cause any anxiety for me.''*

Self-efficacy

All participants described that they were able to participate in the training sessions, and that they felt they did well. Some participants reported that their sense of self-efficacy grew throughout the training sessions, starting with feeling unsure about their ability at the first training session, to feeling accomplished after the second or third session. Some of these participants related their initial apprehension to comorbidities.

> P031 *''I have COPD and you're aware that there are situations in which you may have to drop out. And in that sense, this could have happened to me in this training as well. Fortunately, it didn't.''*

Finally, one participant provided an example of how she felt after the training sessions.

> P022 *''Well, I can say that I feel I did well. It brings you joy if you have something like that* (decreased strength in one leg due to a comorbidity) *and you're still able to catch yourself well.''*

Perceived effectiveness

This construct is understood as the extent to which participants perceived changes in their physical or psychological functioning, and attributed this to the training. Perceived training effects can be divided into physical and psychological effects. For most participants, recognizing physical training effects was not straightforward. Some participants clearly described improvements in their daily activities which they attributed to the training, such as improved walking ability or balance.

> P068. *''I've been walking my son's dog a lot lately. (…) I've noticed that because of that* (training) *I'm steadier on my legs. Like this morning when I walked him, I had to walk downhill. And before I did the balance training, I would have thought 'Oh I have to be careful', but now I just know: I have to move like this, I have to put my foot here. And I can do this.''*

Still, most participants expressed that their physical abilities had remained the same, and wondered how they could have noticed possible changes due to training. For most, falling or stumbling was not a daily occurrence to begin with, and as the interviews took place shortly after training completion, they noted that potential changes were not easily identifiable in this short term. This was neither described as a barrier nor a facilitator to participating in the PBT.

> P031. *''But if my balance has improved because of it, that's very hard to determine, because I don't fall very often. That I broke my wrist due to a fall was more of an accident.''*

Psychological effects were described as much more apparent and positively related to the acceptability of the intervention. Most participants expressed that the training had helped them gain confidence and improved self-efficacy, during the training sessions and in everyday life. They attributed this to how during the training they experienced that their body was capable of more than they expected.

> P068. *''Especially the first time I noticed that I was quite insecure. (…) And that was more related to my confidence, which had been damaged. And I noticed after a few times that I, because of the training actually, gained some confidence. That I got more confident in my body.''*

Ethicality

This construct may not only be related to the extent to which the PBT was perceived to be a good fit with the participant's value system, but also to their expectations of the PBT. Most participants reported that anything they could do to prevent future fall incidents was viewed as valuable.

> P069 *''Well, I was really glad about it, because I thought 'anything I can practice or do to help me fall less, will be helpful' ''*

Some participants found it hard to describe if falls prevention in general fit within their value system. Often participants related this to not having heard or thought about falls prevention until they were approached by the study team.

> P032 *''I hadn't heard or read anything about it before, I started this without expectations.''*

Some also described having thought about it but not knowing who to approach about the topic, or not considering that they needed it. The lack of prior knowledge or expectations about the PBT was not perceived as a barrier to participating. Conclusively, some participants valued being able to contribute to a scientific study.

Intervention coherence

All participants were able to recognize and describe the aim of the intervention to a certain degree. For example:

> P023 *''In my own words? That you're more able to keep your balance. And it has worked.''*

Another participant provided a more detailed explanation of what she perceived as the aim of the intervention.

> P043 *''To be able to recover, when you've lost balance. I think that that was the aim. That you're able to react; your body, your legs, or even with the help of an arm swing. Faster recovery to regain your balance.''*.

A factor that repeatedly emerged related to coherence of the intervention, is 'intervention validity'; understood as the extent to which participants perceived that the intervention had a good fit with its' aims. Most participants who discussed this topic, described the intervention as valid and perceived this as a facilitator to participating in PBT.

> P026 *''A few times I nearly fell, but then you're able to correct this and it's a beautiful simulation of what can happen in real life. Especially when the treadmill belts don't run at the same speed, when one decelerates while the other continues. Then you get an effect like you're experiencing a slip.''*

However, a few participants also questioned if it was at all possible to prevent a future fall incident, reasoning that a fall occurs too sudden to make any preventive adjustments.

Burden

Participants agreed that the burden of participating in PBT was acceptable. The training was perceived as challenging, but not too challenging. Some participants positively related this to the way the training sessions were structured, providing a gradual and personalized increase in challenge.

> P069 *''No, there was a good and gradual increase in challenge. They started the training quite easy and then it gradually became harder. It was very well structured.''*

Most effort was required to maintain or regain balance, and to stay focused throughout the session. Participants reported that the required physical stamina was not an important contributing factor to the perceived training load. When mentioned, participants described that the unexpected balance perturbations were perceived as more challenging than the first part of the training, where they could anticipate on what would happen next.

> P022 *''The hard part was when it was sudden, unexpected. Going left, right, forward. That was, well, not hard; you can get it done, but you have to make sure you don't fall, even if you're in a safety harness.''*

Opportunity costs

Participants agreed that no activities had to be given up to participate in the PBT. Most related this to having enough time after retirement. The possibility to schedule the training sessions in consultation with the trainer instead of having fixed training times was reported as an important facilitator. Most participants accepted travelling to the training location as a fact and did not describe this as either a barrier or a facilitator. A few participants found the central location of the hospital a positive factor, as this was easy to reach using public transportation. Another few participants described that any location outside walking distance provided a challenge and a potential barrier, as they were no longer able to drive a car and had to rely on public transportation or family members to get there. As for the training location being inside a university hospital, this was mostly perceived as an advantage. Participants often described that they thought this was the logical place where they expected to find the right equipment and expertise for this kind of training. Some also mentioned that they regarded the university hospital as a familiar institute, and therefore easy to find.

Training setting

This additional theme was identified throughout the interviews, and includes specific factors related to the setting of the PBT. The PBT took place in a specific setting with specialized technological equipment (see **Figure 5.1**) inside a university hospital. Most participants described that they experienced the technological training equipment as positive, as a surprising and interesting novelty. One participant explained that she felt slightly overwhelmed when she first saw the training equipment, but this improved when she got a more detailed explanation of what was going to happen and when she experienced the training for herself.

> P031. *''The setting was very surprising. The fact that you're walking on a treadmill in an environment that moves with you. I thought it was a very extraordinary experience.''*

Most participants described the virtual environments that were used during training as surprising and positive. A few participants expressed a preference for the first virtual environment (the forest road), describing that this felt more friendly and stimulating than the second, more industrial environment.

The individual nature of this training was clearly valued by some participants, while others were ambivalent about this. Participants who indicated a preference for training individually, described that they enjoyed being able to really focus on the training itself without distractions from other people or the environment, and to train at their own level. Some also reasoned that this increased the potential of the training to be effective.

> P068*. ''This, the balance training, is not something you can do in a group. And I just thought it was very pleasant, because you're focusing on yourself. You're focused on what is going to happen, and you can feel everything that happens (…). And I just think that it is much more pleasant this way, and it will be more helpful.''*

While most participants preferred training individually, some described that they were curious to see how other people performed during the training sessions. Additionally, two participants would have appreciated the opportunity to compare and discuss fall-related experiences with peers.

A numeric rating scale (NRS) was used as a tool to individualize training progression. During the training sessions, participants were regularly asked to score how challenged they felt at that moment, ranging from 0 (not challenged at all) to 10 (highest perceivable challenge). Participants described mixed experiences with this system. Some found the scoring easy and even helpful and described that it helped them gain insight in how they felt at that moment. Others described that they had trouble translating their subjective experience to a number that meant little to them. Overall, the NRS scoring was not perceived as an important barrier or facilitator.

Discussion

The aim of this study was to evaluate the acceptability of a PBT program as perceived by older adults, using the TFA. Gaining understanding of the acceptability of PBT in older adults with a recent history of falls is imperative to enable and optimize future implementation of PBT in clinical practice.

The results indicate that this PBT protocol is perceived as acceptable by older adults with a recent history of falls and highlight key areas for potential future modifications. Besides the TFA, one additional theme emerged from the data, which includes challenges specific to the training setting such as preference for group training in some participants and travel to the training location.

Participants valued being able to feel safe during training. Most reported that this was accomplished by using the safety harness, the physical presence and guidance from the trainer, and individualized training progression. These results reflect those of Miller *et al.*, who evaluated the perceived acceptability of conceptually challenging exercise raining to older adults, including dynamic balance tasks with external perturbations.[21] The novelty of the training and technology were regarded as a positive factor contributing to enjoyment by most participants. However, as in Miller's study, some participants reported feeling initially apprehensive or anxious towards the new training. Okubo *et al.*[11], related elevated anxiety levels during PBT to the unpredictability of the perturbations. We previously hypothesized that a more gradual training progression over multiple sessions may help participants build confidence and alleviate anxiety while still being effective.[22] This hypothesis is partially confirmed by our current findings, which indicated that self-efficacy improved over time. Participants who initially experienced anxiety also reported that this improved over time, and individualized training progression was reported as a facilitator to feeling safe during training. As unexpected perturbations are key for task-specific PBT, the trade-off between measures to alleviate anxiety while still achieving the desired training stimulus should be considered in future implementation. Our findings suggest that this may be particularly important at the start of training.

Perceived psychological effects in the form of increased confidence in balance abilities, and increased self-efficacy in daily life were often reported. Consistent with previous studies on falls prevention interventions, participants described that the PBT helped them gain insight in their ability level and were pleasantly surprised by their ability.[21,23] This is important as maintaining balance confidence can help avoid undue activity avoidance and subsequent disability.[24] Moreover, decreased balance confidence has been identified as a predictor for future falls.[25] While participants generally felt they did well during training, perceived physical effects in daily life were less apparent. Participants questioned how they would notice physical training effects, as falling was not a daily occurrence for them to begin with. In part, this may have been related to the interviews taking place shortly after training completion, leaving little time for participants to experience training effects. However, we hypothesize that this may also be related to the perceived intervention validity and ethicality.

While the topic of perceived intervention validity emerged in most of the interviews, participants views were mixed. Some described that they perceived the intervention valid as it clearly simulated daily-life balance perturbations. In contrast, other participants did not discuss PBT specifically, rather questioned if it was at all possible to prevent a fall in daily life, describing that falls occurred too sudden to intervene or were 'just accidents that could happen to anybody'. The belief that falls are just bad luck, and disbelief that they are preventable is well-known from the literature.[26-29] A review by McInnes *et al*. recommended that these beliefs should be countered prior to intervention.[30] While all participants in our study had recently fallen and agreed to participate in the current intervention, none of them actively sought to participate in falls prevention before. Participants described that they had previously given little or no thought to falls prevention, or that they did not think they needed it. This is in line with previous studies, indicating that those who have previously fallen are not necessarily more likely to be receptive to falls prevention interventions.[31,32] Another study described that older adults may reject the idea that they need falls prevention because they regard themselves as healthy and able to manage.[33] PBT being a relatively new intervention, it may be assumed that this intervention is even less known to potential participants, thus increasing the challenge to reach the target population. Some participants reported that being informed by or talking to a health practitioner about the PBT, and being approached by the researchers, prompted them to consider falls prevention or to finally participate. This corroborates findings from Yardley *et al*., reporting that a personal invitation by a health practitioner may be a facilitating factor to participation in falls prevention.[34] Our findings suggest that these factors may be particularly important to consider for PBT or any relatively unknown intervention, to effectively reach older adults.

Some participants clearly expressed a preference for training individually. Others described that they would have been curious to see how others performed during the training sessions, or to share fall-related experiences with others. Promoting the social value of falls prevention interventions has been previously identified as a facilitator.[30] Additionally, watching or partnering with a peer completing the same exercises may facilitate participation and improve older adults' confidence for their own attempt.[21,35,36] As PBT is currently not suited for a group intervention, it may be considered to provide a medium between individual and group training, while simultaneously addressing the initial apprehension or anxiety experienced by some participants. Specifically, this could be achieved by providing new participants with a video of a peer completing the exercises before their own participation, or combining training sessions of two participants where they can see each other perform and share experiences. Conclusively, hearing experiences from peers who completed the PBT might also improve perceived intervention validity and ethicality for future participants.

Finally, a practical factor that should be considered is travelling to the training location. As is the case with most set-ups for PBT, the equipment used in this program is not yet available in many locations. Some participants described that while they were able to attend the PBT sessions, travel was a potential barrier. This barrier is well-known in this population, as some older adults are no longer able to drive a car themselves and thus depend on family members or public transportation.[34,37]

Strengths and Limitations

To our knowledge, this is the first study to use the TFA to examine older adults' perceived acceptability of PBT. Using the TFA enabled a systematic approach to define and assess intervention acceptability.[9] While triangulation was applied in data collection as well as data analysis to increase trustworthiness of the research findings, it should be noted that one researcher (MG) was involved in the PBT sessions, as well as most of the interviews. In future studies, it may be considered to include a dedicated interviewer separate to the intervention team. A few limitations should be considered when interpreting the results of our study. First, the PBT intervention was applied in a research setting, meaning that some specific factors, such as willingness to pay for participation in the intervention, were not evaluated. Second, the results only reflect the perceived retrospective acceptability of the PBT. Further research is necessary to evaluate prospective and concurrent acceptability, to further elucidate what factors motivate or prevent older adults from participating in PBT.[9]

A final consideration is that due to COVID-19 related restrictions, 7 out of the 16 interviews in this study were telephone interviews. While face-to-face interviews are often regarded as the gold standard, there is little evidence that quality of findings collected through telephone interviews is compromised.[38] Consistent with Sturges *et al.*, we identified no clear differences between data collected through face-to-face interviews compared to telephone interviews in our study.[39]

Conclusions

In conclusion, findings from this study indicate that a technology-assisted PBT program is acceptable to older adults with a recent falls history. Enjoyment of the intervention, being able to feel safe, perceived psychological effectiveness and individualized training progression were identified as important factors contributing to the perceived acceptability. Increasing the social aspect of training and sharing experiences of peers may be considered to enhance acceptability to new participants who initially feel apprehensive or anxious about their ability to participate, or who are unsure what to expect. Raising awareness of the importance and possibilities of falls prevention training in general is a challenge in this population.

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Supplemental file 5.1

Interview guide Acceptability of Perturbation-based balance training (PBT)

This interview guide gives an overview of the opening questions for each topic. The interviewers used a range of follow-up questions to obtain more information which were adapted and used as appropriate in each interview.

Theoretical framework
Opening question: Can you tell me how you experienced the training?

Affective attitude

How do you feel about the training?

Burden

To what extent did you find the training difficult?
To what extent did you find it challenging?

Self-efficacy

How do you feel you did during the training?

Perceived effectiveness

To what extent did you notice effects from the training (during training and in daily-life)?

Ethicality

To what extent did the training fit with your values? To what extent did it fit with your views on falls prevention?

Intervention coherence

Can you explain to me what the goal of the training was?

Opportunity costs

To what extent did you have to give up other activities or values to participate in the training?

Context-specific factors

What are your thoughts about…
… the location of the training?
… training individually, as opposed to in a group?
… the technological equipment used in the training?
… the scoring system that was used during training?
… the way the training was supervised?

The effect of perturbation-based balance training on balance control and fear of falling in older adults: a randomized controlled trial

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Submitted

6

Abstract

Background

Perturbation-based balance training (PBT) is an emerging intervention shown to improve balance recovery responses and reduce falls in everyday life in older adults. However, perturbation interventions were heterogeneous in nature and need improvement. This study aims to investigate the effects of a PBT protocol that was designed to address previously identified challenges of PBT, on balance control and fear of falling in older adults at increased risk of falling.

Methods

In a single-blind randomized controlled trial, the additive effects of a PBT protocol to usual care on balance control and fear of falling are evaluated. Community-dwelling older adults (age ≥65 years) who visited the hospital outpatient clinic due to a fall incident were included. Participants received PBT in addition to usual care (referral to a physiotherapist) versus usual care alone. PBT consisted of three 30-minute sessions in three weeks. Unilateral treadmill belt accelerations and decelerations and platform perturbations (shifts and tilts) were applied during standing and walking on the Computer Assisted Rehabilitation Environment (CAREN, Motek Medical BV). This dual-belt treadmill embedded in a motion platform with 6 degrees of freedom, is surrounded by a 180^{o} screen on which virtual reality environments are projected. Duration and contents of the training were standardized, while training progression was individualized. Fear of falling (FES-I) and balance control (Mini-BESTest) were assessed at baseline and one week post-intervention. Primary analysis compared changes in outcome measures between groups using Mann-Whitney U tests.

Results

Eighty-two participants were included (PBT group n=39), with a median age of 73 years (IQR 8 years). Median Mini-BESTest scores showed a trend towards improvement but changes were not significantly different between groups (*P*=0.87). FES-I scores did not change in either group.

Conclusions

Participation in a PBT program including multiple perturbation types and directions did not lead to different effects than usual care on balance control or fear of falling in community-dwelling older adults with a recent history of falls. More research is needed to explore if more specific populations may benefit from PBT to improve balance control, and which outcomes are most suitable to measure training effects on balance control.

Introduction

Falls annually affect one in three adults over 65 years.[1,2] In 2019, approximately 109.000 Dutch adults over 65 years visited the emergency department due to a fall incident, resulting in over 1 billion euros of direct medical costs.[3] Falls are a leading cause of injuries and hospitalization among older adults and can have many physical and psychological adverse consequences.[4,5] The risk of falling increases with age and can increase even further in the presence of additional risk factors. An important and modifiable risk factor for falls is balance control.[6,7] Having experienced a fall incident is another prognostic factor, which greatly increases the risk of sustaining future falls (odds ratio (OR) 2.8 for all fallers, and 3.5 for recurrent fallers).[6,8,9] Consequently, older adults who have fallen are also more likely to develop fear of falling, and to experience a further decline in balance control after their fall incident.[10,11] Since fear of falling and impaired balance control both increase the risk for falls, this illustrates how a single fall incident can lead older adults to end up in a negative cycle.[10] Given that the number of older adults is currently increasing rapidly, the burden of falls will continue to increase. Therefore, it is essential to develop interventions that make older adults more resistant to fall incidents.

Balance training is reported to effectively improve balance control and reduce fall rates in older adults by approximately 24%.[12,13] Nonetheless, there are some drawbacks to conventional balance training interventions. Firstly, it should be understood that ‘balance control’ is an umbrella concept that can be subdivided into multiple motor skills[14], each of which is vital to perform activities of daily living. As described by Berg *et al.*, balance control can be divided into three general categories: maintaining a position (static balance control), adjusting voluntary or anticipated movements (proactive balance control), and reacting to external or unexpected balance perturbations (reactive balance control).[15] Conventional balance training programs do not typically address reactive balance control but focus mostly on proactive balance control.[16] However, approximately 60% of falls in older adults result from an unexpected external perturbation during walking, such as a slip or trip.[17] As the recovery actions needed to prevent such falls rely mostly on reactive balance control, the task-specificity of conventional balance training may be limited.[18,19] Additionally, conventional balance training requires a relatively high number of training sessions to be effective, and retention of training effects is hard to accomplish.[20-22] As such, research to optimize balance training interventions for older adults continues.

In recent years, perturbation-based balance training (PBT) has gained increasing interest as an intervention which is more task-specific to the recovery actions needed to prevent falls from unexpected balance perturbations. PBT aims to improve reactive balance by repeatedly exposing participants to destabilizing perturbations in a safe and controlled environment. Results from two meta-analyses indicate that PBT can significantly reduce daily-life fall rates by 46% and 52%, respectively.[23,24] Studies have also found beneficial effects of PBT on the number of laboratory-induced falls[25-27], various measures of balance recovery (e.g., margins of stability after perturbation or time to stabilization of center of pressure)[25,27-32], and balance control (e.g., limits of stability, five-step test, and Berg Balance Scale (BBS)).[33-36] Additionally, PBT may have the potential to be effective with a low training dose (one to four training sessions), which could make PBT a more efficient alternative to other interventions.[37-40] In this study, the effects on balance control will be measured using the Mini Balance Evaluation Systems Test (Mini-BESTest). The Mini-BESTest is a comprehensive clinical balance test that besides tasks related to static balance control and proactive balance control, also includes tasks requiring reactive balance control. Compared to the BBS, the Mini-BESTest showed higher accuracy for identifying community-dwelling older adults with a history of falls, without the ceiling effect the BBS has in this population.[41-43]

While current studies report promising results of PBT, they are heterogeneous in terms of training parameters, study populations, and outcomes. Further study is required to help develop effective training protocols that are tolerable and acceptable to the target population. To build upon the literature, this study will address some previous identified challenges of PBT. Firstly, studies have suggested that PBT training effects may be limited to the specific condition that was trained[39,44], or only partly generalizable to different conditions.[18,45] This is a factor that should be addressed to ensure a beneficial impact on everyday life, where falls can happen in all kinds of conditions. A potential strategy that has been proposed to improve the generalization of adaptations to PBT is to include a variety of training conditions (for example multiple perturbation types and directions).[46] Other challenges include the physical tolerability and acceptability of PBT for older adults. Not all older adults may initially be able to tolerate the required training dose of PBT, which may lead to anxiety or inability to physically cope with the perturbations.[40] Anxiety during training is a factor that was found to limit acceptability and increase drop-out rates, and thus limit the effectiveness of PBT.[32] A proposed method to improve both physical tolerability as well as acceptability is to progressively increase training intensity (e.g., perturbation magnitude or unexpectedness) in a manner that is tailored to the individual.[26,40,46]

In this study, we evaluate the effects of a PBT protocol[47] that was designed to address these previously identified challenges of PBT, on balance control and fear of falling in older adults with an increased risk of falling based on a recent fall incident.

Methods

Study design and participants

A detailed description of the full study protocol was previously published.[47] In this single-blinded (outcome assessor) randomized controlled trial (RCT) PBT was offered to community-dwelling older adults (≥65 years). Older adults were eligible to participate in the study if they had experienced a fall in the previous three months, had therefore visited the hospital outpatient clinic, and were able to walk without a walking aid for ≥15 minutes. Exclusion criteria were diagnosis of any disease or disorder that may affect the safety of training (e.g., osteoporosis, recent fracture or severe contusion of the lower extremities, back or shoulders, or severe cardiopulmonary disease), falls caused by actions of third parties or during exercise activities, falls due to syncope, and use of medication known to increase falls risk.[48] Potential participants were also excluded if they were unable to follow instructions due to cognitive problems, unable to provide written informed consent or to communicate in Dutch. The study intervention and measurements were conducted between March 2019 and August 2021 at the physiotherapy department of the Maastricht University Medical Center, The Netherlands. Study outcomes were measured at baseline and one week post-intervention. Ethics approval was obtained from the Medical Ethics Committee azM/UM (METC18-049).

Interventions

Participants were randomized to receive PBT as an add-on to usual care versus usual care alone. Usual care consisted of physiotherapy referral by the medical doctor if indicated. It was up to the participant to visit the physiotherapist after referral, and the content of the treatment was decided by the medical doctor and physiotherapist together. During study visits, the outcome assessor routinely monitored if and how often each participant had visited their physiotherapist, and what components (i.e., strength training, mobility exercises, balance exercises) were included in the physiotherapy treatment.

Participants referred to the experimental group received usual care as described above, and three 30-minute sessions of PBT additionally. The PBT sessions were given once a week for three consecutive weeks using the Computer Assisted Rehabilitation Environment (CAREN, MOTEK Medical BV). The CAREN is a dual-belt treadmill embedded in a motion platform with 6 degrees of freedom. The treadmill and motion platform can both provide unexpected balance perturbations, such as unilateral treadmill belt accelerations or decelerations, and platform translations and rotations in various directions. This is combined with a 180-degree screen on which a virtual reality environment is projected to make training more immersive. Participants wear a safety harness during training sessions, preventing the knees from hitting the ground in case of an unsuccessful balance recovery.

Training procedures

The first training session on the CAREN started with a familiarization procedure, where the participant could get used to the system by walking on the treadmill in the virtual environment. Participants reported a numeric rating scale (NRS) score for how comfortable they felt when walking on the CAREN before and during familiarization (0; very uncomfortable to 10; fully comfortable). If a score of 7 or higher was reached, the familiarization procedure was deemed complete. This was expected to occur within 6-7 minutes.[49]

After this, each participants' comfortable walking speed was determined using a ramp protocol. Subjects started walking at 0.5 m/s and speed was gradually increased until the subject said 'stop' when their comfortable walking speed was reached. The participant then walked unperturbed at this speed for approximately one minute to check if any adjustments needed to be made.

Consecutive sessions started with a warm-up during which the participant walked unperturbed on the treadmill at their comfortable speed (determined during the first session) for approximately 3 minutes and got readjusted to the system. Each training session consisted of three parts: gait adaptability, static and dynamic reactive balance control (of which details are given below). During training, participants were regularly asked to rate how challenging it was to maintain their balance on an NRS score (0-10; 0 = not challenging at all, 10 = unable to maintain balance). To ensure that the training was challenging but acceptable and tolerable for each participant, the aim was to train at a difficulty level between 6 and 9 (challenging to very challenging) on the NRS. Training progression was based on these NRS scores, and each participant's ability to manage the perturbations. Training difficulty was progressed by increasing the perturbation intensity and walking speed. During the second and final training sessions, cognitive and motor dual tasks (e.g., counting backwards in steps of 7, hitting targets in the virtual environment) could also be added to increase training difficulty. Participants were aware that there would be 'various challenges to their balance' during the training, and were instructed to recover their balance and to try to continue walking. Participants were naïve to the timing and the order of perturbation types that would be applied. Training adherence was monitored throughout the study, and participants were encouraged to reschedule any missed training sessions.

1. Gait adaptability

Participants walked in a virtual environment of a path through a forest, with various slopes and turns. Both the incline/decline of the slopes and the sharpness of the turns had a standardized starting level of 20% (out of 100%), which was then progressed in steps of 5% to 15%. Each 5% increase in difficulty level means an increase in the incline, decline and rotation of 0.5 degrees.

2. Static reactive balance

Participants stood on the CAREN while the platform and treadmill belts provided sudden perturbations. The platform could shift (move in the horizontal plane) or tilt (move into a sloping position) to anterior, posterior, left and right. The treadmill belt could unilaterally accelerate from standstill. In the second and third parts of the first training session, training difficulty started at the lowest difficulty level for each participant and could be progressed individually over 7 difficulty levels.

3. Dynamic reactive balance

Participants walked on the treadmill at their comfortable walking speed, while the above-mentioned platform and treadmill perturbations were applied. The treadmill perturbations consisted of unilaterally accelerating or decelerating the treadmill belt for short periods of time (0.2–0.7 seconds).

Measurements

Study outcomes were measured at baseline (T0) and after 4 weeks, which was one week after the final training session for the PBT group (T1), by an outcome assessor who was blinded to treatment allocation. Demographic data (age in years, sex, body height (cm) and weight (kg)) was collected at baseline, including retrospective falls incidence over the previous 12 months. A fall was defined as 'an event which results in a person coming to rest inadvertently on the ground or floor or lower level'.[50] An adapted version of the 'falls history questionnaire' as presented in the book *'Falls in older people: risk factors and strategies for prevention'* was used.[51] This questionnaire records if a fall has occurred in the previous 12 months, where it has happened, what the perceived cause was, and if and what kind of injuries were sustained. The outcome assessor filled in this questionnaire together with the subject to make sure that the recorded data was as comprehensive and clear as possible. Adherence to training in the PBT group was defined as attendance to the training session and completion of at least two out of three training parts.

Balance control

The main outcome in this study was balance control, assessed on the Mini-BESTest. The Mini-BESTest is a comprehensive measurement tool to assess balance in community-dwelling older adults.[43] The test is divided into four categories: anticipatory balance control (0-6 points), reactive balance control (0-6 points), sensory orientation (0-6 points) and dynamic gait (0-10 points). There are a total of 14 tasks which are scored on a three-point scale (0-2), with a total score ranging between 0 and 28 points. A higher score corresponds with better balance control. The Mini-BESTest has good reliability and validity, and a significantly smaller ceiling effect in community-dwelling older adults compared to the BBS.[41,42] The minimal detectable change (MDC) at the 95% confidence level is 3-4 points.[52-54] Cut-off values indicating increased fall risk for the Mini-BESTest are age dependent; ≤25 points for people 60 to 69 year of age, ≤23 points for 70 to 79 years, ≤22 points for 80 to 89 years and ≤17 points for 90 years and older.[55]

Fear of falling

Fear of falling was measured with the Falls Efficacy Scale International (FES-I, Dutch version). This version of the falls efficacy scale is a 16-item questionnaire developed to determine if a person has confidence in their ability to perform a range of daily activities without falling. It has been adapted to be more suited to older adults, including a range of activities from very basic to more complex.[56] The questionnaire will be filled in by the subject with the help of the outcome assessor. Sixteen items are scored on a four-point (1-4) scale, with a maximum score of 64 points. A higher score corresponds with a greater fear of falling. Cut-off points of 16-22 points for 'low concern' and 23-64 points for 'high concern' about falling have been described.[57] The Dutch version of the FES-I has good reliability and validity and discriminative power in older adults.[56-59]

Sample size and randomisation

Sample size was calculated in G*power 3.1.9.2 and was based on the primary outcome of this study, difference between group means on balance measured with the Mini-BESTest post-intervention. The effect size *d* (0.61) was calculated based on values from an article with a similar study population and an intervention aimed at improving dynamic balance control.[52] We assumed that changes from baseline to post-intervention would be in the favour of the PBT group. Sample size was based on a one-tailed independent samples t-test, with an α of 0.05, power (1-β) of 0.80 and allocation ratio of 1. This resulted in a required sample size of n=72. Accounting for an expected loss to follow-up of 10%, the final sample size is n=80. Sample size was estimated conservatively, making no assumptions about the correlation between predictors (group allocation and baseline score) added into the model and the outcome variable.

Participants were randomized using a 1:1 ratio stratified block randomization (block sizes 2 and 4). Randomization was stratified based on sex (male/female) and number of falls during the previous year (1 versus 2 or more falls). The randomization sequence was generated using an online random number generator. Allocation was concealed by using sequentially numbered, sealed opaque envelopes. The allocation sequence list was kept in a locked drawer, which could only be accessed by the principal investigator.

Statistical analysis

Descriptive statistics are presented as means and standard deviations (SD) or as medians and interquartile ranges (IQR), depending on the normality of the data. Categorical data is presented as frequencies (n) or percentages (%). Data was analysed on an intention-to-treat basis (missing data imputed using single stochastic regression imputation). Mann-Whitney U tests were used to determine if there was a significant between-group difference in Mini-BESTest or FES-I score change between baseline and follow-up (ΔMini-BESTest or ΔFES-I, respectively). To compare proportions or percentages between groups, the chi-square test was used. A multiple regression analysis was performed to explore potential confounding variables in the association between group and ΔMini-BESTest. Variables (age, sex, previous falls, FES-I at baseline, if the participant visited a physiotherapist and if their treatment included gait/balance training between baseline and post-intervention) were added (enter method) to the model, and variables that resulted in a ≥10% change in the regression coefficient of the main determinant were eligible for inclusion in the model. The variable contributing the most (≥10%) was included in the model first, and this process was repeated for each following variable until there were no more potential confounding factors.[60] In all analyses, statistical significance was set at $P<0.05$. Data was analysed using the Statistical Package for the Social Sciences version 23.0 (SPSS, Chicago, Ill., USA).

Results

Between March 27th, 2019 and July 8th, 2021, 82 participants were included, of which 39 were randomly assigned to the PBT group (8 men, 31 women) and 43 to the control group (9 men, 34 women). The median age of the participants was 73 years (IQR 8 years). Some 49 participants experienced 1 fall during the previous year, 19 participants had fallen twice and 14 participants had fallen 3 or more times. No significant between-group differences in demographics and baseline characteristics of the participants was found (see **Table 6.1**). Six participants withdrew from the study; 2 (PBT group) due to restrictions related to the COVID-19 pandemic, 2 due to personal reasons (control group) and 2 no longer wanted to participate when they were randomized to the control group. Mini-BESTest values of five more participants (2 control and 3 PBT) are missing due to restrictions related to the COVID-19 pandemic. **Figure 6.1** gives an overview of the flow of participants from eligibility assessment to each stage of the study.

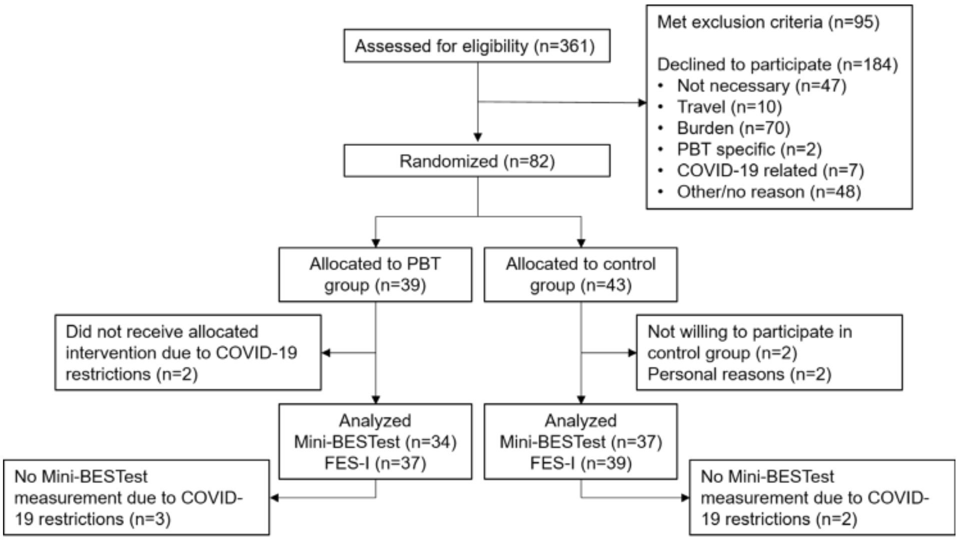

Figure 6.1 CONSORT flow-diagram of participants.
Overview of participant flow from inclusion to the final measurements, including reasons for non-inclusion or drop-outs. PBT = perturbation-based balance training. Mini-BESTest = Mini Balance Evaluation Systems Test. FES-I = Falls Efficacy Scale International. Not necessary = participant did not think they needed an intervention. Travel = participant did not want to participate due to travel issues. Burden = participant considered the time investment too high (often in combination with other treatment appointments). PBT-specific = two participants did not wish to participate for reasons related to the PBT training, specifically the safety harness. COVID-19 related = participants did not wish to participate due to the COVID-19 pandemic.

Training characteristics

Adherence to the training was 93.7% over all training sessions (104 out of 111 total scheduled sessions), of which 100 sessions were fully completed. Of the 37 participants who started PBT training, 31 (83.8%) attended all three training sessions. Six participants missed one or two training sessions, due to co-morbidities (n=3), scheduling issues (n=2) or feeling that their balance was too good for the training (n=1). One participant reported a training-related adverse event of experiencing knee pain after making a misstep during the training session, which resolved without intervention within two days after the training session. By the end of the first session, participants on average reached difficulty levels 4 (range 2-6) and 2 (range 1-5) for standing and walking perturbations respectively (7 being the highest difficulty level). By the end of the third training session, participants on average reached level 6 (range 3-7) for standing perturbations and level 4 (range 2-7) for walking perturbations.

Table 6.1 Participant characteristics.

	Control (n=43)	**PBT (n=39)**	***P*-value**
Age (years)	73 (8)	73 (10)	0.77
Sex (male/female)	9/34	8/31	0.96
Height (cm)	164.0 (10.0)	161.0 (11.6)	0.50
Weight (kg)	69.7 (18.5)	71.1 (19.0)	0.73
BMI (kg/m_2)	26.3 (4.2)	27.0 (5.0)	0.71
Falls in previous 12 months (1, 2, ≥3 (n))	1 (25), 2 (12), ≥3 (6)	1 (24), 2 (7), ≥3 (8)	0.90
Physiotherapy T0-T1 (yes/no)	19/24	20/19	0.52
Gait/Balance training T0-T1 (yes/no)	4/39	4/35	0.88

Data is presented as median (interquartile range) or frequencies. Physiotherapy T0-T1 and Gait/balance training T0-T1; if participants received any physiotherapy sessions between T0 and T1, and if this training included gait and/or balance training. BMI = Body Mass Index.

Assumptions

All assumptions for statistical tests were met. An analysis of standard residuals showed that the data contained one outlier on the Mini-BESTest at T1. As this score accurately reflected the performance measured for this participant, this value was not removed from the analysis.

Outcomes

Table 6.2 shows outcomes at baseline (T0) and post-intervention (T1) for both groups. Mini-BESTest scores at T0 and T1 are presented in **Figure 6.2**. Baseline Mini-BESTest scores were 23 (4) points in both groups, baseline FES-I scores were 20 (8) and 20 (7) points for the control group and PBT group, respectively (median (IQR)). Median Mini-BESTest scores increased in both groups, however these change scores were not significantly different between groups (*P*=0.87). No significant between-group difference in FES-I change scores was found (*P*=0.85).

Multiple regression analysis was performed to explore and correct for potential interacting or confounding variables (age, sex, previous falls, FES-I at baseline, physiotherapy T0-T1 and Gait/Balance training T0-T1) in the association between group and ΔMini-BESTest, and between group and ΔFES-I. This analysis revealed that there was a significant interaction effect of age and receiving physiotherapy on the association between group and change in Mini-BESTest. Age also acted as a confounder in the relationship between group and change in FES-I. Adding these variables to the models did not result in a significant association in either model. Full regression analysis results and tables are reported in **Supplemental File 6.1**.

Table 6.2 Outcome measures at baseline and post-intervention.

	Control			PBT			
	T0	**T1**	**change**	**T0**	**T1**	**change**	***P***
Mini-BESTest (0-28)	23 (4)	24 (4)	1 (3)	23 (4)	25 (5)	1 (3)	0.87
Anticipatory balance control (0-6)	5 (1)	5 (2)	0 (1)	4 (1)	5 (2)	0 (1)	0.45
Reactive balance control (0-6)	4 (2)	5 (2)	1 (2)	5 (2)	5 (2)	0 (2)	0.28
Sensory orientation (0-6)	6 (0)	6 (0)	0 (0)	6 (1)	6 (0)	0 (0)	0.91
Dynamic gait (0-10)	8 (1)	9 (2)	1 (1)	8 (1)	9 (2)	0 (1)	0.55
Increased fall risk (%)	65.1	46.5	18.6	56.4	43.6	12.8	0.53
FES-I (16-64)	20 (8)	20 (7)	0 (3)	20 (7)	19 (7)	0 (3)	0.85

Outcome measures (range of possible scores) for the control- and PBT-group at T0 (baseline) and T1 (post-intervention). Change = difference between pre- and post- outcome values. Mini-BESTest = Mini Balance Evaluation Systems Test. FES-I = Falls Efficacy Score International. Increased fall risk = the percentage of participants at increased risk for falling based on their Mini-BESTest score. Data is presented as median (IQR) or percentages.

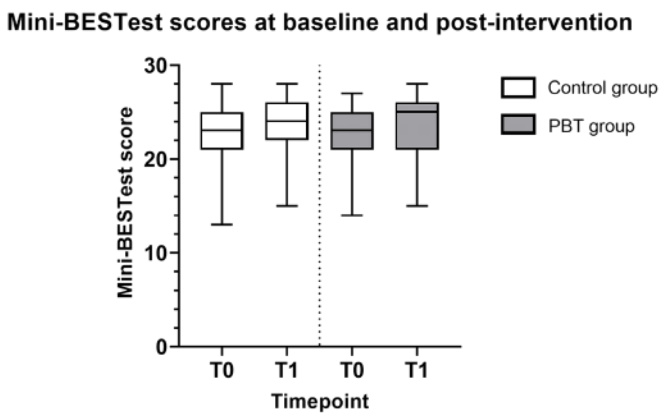

Figure 6.2 Mini-BESTest scores at baseline and post-intervention in the control- and PBT groups. Mini-BESTest: Mini Balance Evaluation Systems test. T0: baseline, T1: post-intervention.

Discussion

This study evaluated the effects of a PBT protocol in addition to usual care on balance control and fear of falling in older adults with a recent history of falls. We hypothezised that the PBT group would show greater improvements compared to the control group. While median Mini-BESTest scores increased slightly in both groups, these changes were below the threshold for minimal detectable change and were not significantly different between groups. Median falls efficacy scores decreased by one point in the

PBT group but not in the control group, and no significant between-group differences were found. Explorative secondary analysis revealed interactive effects of age and receiving physiotherapy on the association between group and ΔMini-BESTest, while age acted as a confounding variable on the association between group and ΔFES-I. Correction for confounding variables strengthened both associations but did not lead to a significant association with group in either.

The findings of this study do not support our hypothesis that balance control would improve significantly in the PBT group compared to the control group. Similar conclusions were drawn by recent studies comparing the effects of PBT to general balance training or multimodal physiotherapy on clinical measures of balance control (BBS, Timed Up and Go, and Dynamic Gait Index) in healthy community-dwelling older adults.[61,62] As all participants in the present study had recently experienced one or more fall incidents, we expected that this would be reflected in their baseline values for balance control.[11] However, based on median Mini-BESTest scores at baseline just over half (56%-65%) of the participants were considered at increased risk for falls.[55] To our knowledge, the only studies that found significantly greater improvements in measures of balance control after PBT compared to other interventions included populations with neurological conditions such as Parkinson's disease.[34,35] The results of this study, in line with recent literature in healthy community-dwelling older adults, did not show a significant additional effect of PBT to usual care on clinical measures of balance control in community-dwelling older adults who visit a hospital outpatient clinic due to a fall. A potential avenue for future research may be to explore if PBT can be effective to improve clinical measures of balance control in a more specific population (e.g., a population with a higher fall risk based on balance control at baseline).

Transfer of training adaptations to other tasks or contexts is an important challenge of PBT. Studies have shown that transfer of training adaptations can be achieved, but so far only to different conditions for a similar task. For example, studies have found transfer of PBT training adaptations after slip-perturbations on a low-friction moveable platform to a slippery floor[63], or from a treadmill to an overground surface[45], and interlimb transfer of training adaptations in the same perturbation type and context.[64] Therefore, the training protocol in the current study was designed with the aim to facilitate transfer of training adaptations by including a broader range of perturbation types and directions. However, despite each participant being able to progress to higher perturbation levels during training, this did not transfer to significant changes in overall balance control or balance recovery from lean-and-release perturbations in the reactive balance sub score measured with the Mini-BESTest. These results imply that the application of multiple perturbation types and directions in a three-session PBT protocol may not be sufficient to generate meaningful transfer to clinical measures of balance control in community-dwelling older adults with a recent history of falls.

However, as development and optimization of PBT interventions are still emerging research topics, the implications of these findings for transfer of PBT training adaptations should be interpreted cautiously. For one, it should be considered which outcome measures are most suitable to measure training effects on balance control. While a clinical measure of balance control such as the Mini-BESTest may be more feasible to use in clinical practice, more subtle changes after balance training may be more accurately measured by instrumented measures (such as postural sway or gait parameters), as was demonstrated in a recent study by Hasegawa *et al*.[65] More research is needed to determine which outcome measures are sufficiently sensitive to changes in balance control after training, and how they correlate with meaningful changes in balance control for everyday life. Additionally, while studies have shown promising beneficial effects of PBT with a single or few training sessions[26,37,38], there are no strong guidelines on how to modulate training load to attain an optimal effect. More research is needed to determine the optimal training dose, considering not only how to elicit effects on the tasks trained but also transfer of these training adaptations.

No significant between-group differences were found in change of fear of falling measured with the FES-I. Median values at baseline were classified as 'low concern' based on previously determined cut-off values, and stayed the same for the control group and decreased by one point for the PBT group.[57] These findings are in line with a previous study that found no significant group-by-time interaction effects on fear of falling after PBT.[66]

The results of this study show high training adherence rates, one training-related adverse event, and that increasing training difficulty was possible for each participant, confirming the feasibility of this PBT protocol for participants. However, including participants in the study proved challenging. **Figure 6.1** shows that approximately half of the potentially eligible older adults that were approached, declined to participate. This is comparable to the median inclusion rates of 48.5% in falls prevention interventions for older adults, reported by Nyman *et al*.[67] The most prevalent reasons older adults mentioned were that despite their recent fall(s), they did not see themselves as needing falls prevention or balance training, or that the burden of five study visits (including three training sessions) was too high. These reasons are also comparable to common barriers to participation in falls prevention, while only 2 potential participants indicated that they did not wish to participate for reasons specifically related to the PBT.[68]

Limitations

This study was not without limitations. Firstly, restrictions related to the COVID-19 pandemic meant that some adjustments had to be made to the treatment protocol.

The inclusion criterion of having experienced a fall in the previous 3 months was broadened to the previous 6 months to increase inclusion rates and reach the required sample size after a period of lockdown measures. In retrospect, this was the case for a similar number of participants in the PBT and control groups, and if this was of significant influence this would be expected to be visible from the baseline participant characteristics. The same restrictions also meant that some of the follow-up FES-I measurements had to be done over the phone, this was the case for 2 and 3 participants in the PBT and control group, respectively. This data was collected by the same outcome assessor as the baseline measurements, and did not lead to any issues. Second, while common in intervention studies, participants and therapists in the intervention group were not blinded to group allocation. However, therapists providing usual care, outcome assessors and data analysers were blinded. Additionally, the measurements were performed by a blinded outcome assessor that encouraged all participants to give their best effort. A final limitation of this study is that no direct measures of balance control in response to perturbations were applied during training. While this was a conscious choice to enable participants to focus on their training experience, it also means that direct training effects cannot be analysed from this study.

Conclusions

Participation in a PBT program that includes multiple perturbation types and directions did not lead to significantly different effects than usual care on balance control measured with the Mini-BESTest in this population of community-dwelling older adults with a recent history of falls. Fear of falling measured with the FES-I did not change in either group. More research is needed to explore if more specific populations may benefit from PBT to improve balance control, and which outcomes are most suitable to measure training effects on balance control. Additionally, further study is needed to develop clear guidelines on how to modulate PBT training load to attain optimal and transferrable training adaptations.

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Supplemental file 6.1 Regression analysis results

Assumptions

All assumptions for statistical tests were met. An analysis of standard residuals showed that the data contained one outlier (subject 75, standardized residual -3,769). As this was a plausible outcome value, this participant was not removed from the analysis.

Multiple regression analysis was performed to explore and correct for potential interacting or confounding variables (age, sex, previous falls, FES-I at baseline, physiotherapy T0-T1 and Gait/Balance training T0-T1) in the association between group and ΔMini-BESTest, and between group and ΔFES-I. **Table S6.1** shows the results of univariate linear regression, with no significant association between group and ΔMini-BESTest. Multiple linear regression analysis revealed a significant interaction effect of age (participants with above median age showed smaller improvements when in the intervention group, p=0.004), and receiving physical therapy (participants with physical therapy improved less in both groups, this effect was counteracted if participants received physical therapy and PBT, p=0.047). Addition of these factors to the model did not result in a significant association between group and ΔMini-BESTest. No confounding variables were identified.

Table S6.1 Linear regression analysis – the association between group and ΔMini-BESTest.

				95% Confidence Interval for B	
	B	**Std. Error**	**p-value**	**Lower bound**	**Upper Bound**
Constant	1.000	0.339	0.004	0.325	1.675
Group	-0.308	0.492	0.53	-1.287	0.672

The association between group and ΔFES-I was explored in a similar approach, with the same potential interacting or confounding variables (baseline FES-I was exchanged for baseline Mini-BESTest). **Table S6.2** shows the results of univariate linear regression, with no significant association between group and ΔFES-I. No significant interaction effects were found. The addition of age resulted in a 11,1% change in the regression coefficient of the main determinant (group) and was added to the model (**Table S6.3**). The remaining variables were then added to the model corrected for age, but none resulted in a ≥10% change in the regression coefficient thus no more variables were added to the model. The results show that correcting for age strengthened the association between group and ΔFES-I, but this did not lead to a significant association.

Table S6.2 Linear regression analysis – the association between group and ΔFES-I.

				95% Confidence Interval for B	
	B	**Std. Error**	**p-value**	**Lower bound**	**Upper Bound**
Constant	-0.326	0.526	0.54	-1.372	0.720
Group	-0.315	0.762	0.68	-1.832	1.201

Table S6.3 Multiple linear regression analysis – the association between group and ΔFES-I, corrected for age.

				95% Confidence Interval for B	
	B	**Std. Error**	**p-value**	**Lower bound**	**Upper Bound**
Constant	3.336	5.278	0.53	-7.169	13.842
Group	-0.350	0.766	0.46	-1.875	1.175
Age	-0.050	0.072	0.49	-0.193	0.093

General Discussion

7

General discussion

Summary of main findings

The overall aim of this thesis was to further our understanding on the effectiveness and applicability of perturbation-based balance training (PBT) for community-dwelling older adults. This knowledge could underpin the implementation of PBT in clinical practice. In this chapter, we will reflect on our main study findings, discuss methodological considerations, and make suggestions for future research directions.

Firstly, we conducted a systematic review to get a clear overview of available studies on the effectiveness of PBT applied in older adults, and which factors should be considered for application of PBT in clinical practice. The results of this study revealed that PBT seems a feasible and effective approach for falls prevention in older adults with and without neurological disorders in clinical practice (**Chapter 2**). Additionally, we discussed several factors, such as characteristics of the perturbations (type, direction, magnitude, etc.) and the training program (frequency, volume) that could affect the feasibility and effectiveness of PBT for falls reduction in older adults. Next, we hypothesized that, as falls most commonly occur during walking due to unexpected balance perturbations, walking-based balance assessment including walking stability and adaptability to such perturbations could be beneficial for fall risk assessment in older adults. In a cross-sectional study design, we compared unperturbed and perturbed walking trials of older adults with and without a recent history of falls. We found no significant differences in walking parameters or their variability and minor (but not significant) differences in recovery step behavior after the first perturbation, where the group with a history of falls showed slightly delayed and more inconsistent recovery responses. These differences became more pronounced after repetition of perturbations, and the group without a history of falls significantly reduced the number of recovery steps needed across the trials, whereas the group with a history of falls did not. Thus, we concluded that adaptability to repeated perturbations may be a more useful marker of falls history in older adults (**Chapter 3**).

In **Chapter 4** of this thesis, we designed a PBT protocol informed by the factors discussed in **Chapter 2**. In a mixed-methods approach, we embedded a qualitative study in a randomized controlled trial (RCT) to evaluate the acceptability as well as the effectiveness of our PBT protocol in addition to usual care. The results of the qualitative study revealed that perturbation-based balance training is perceived as acceptable by older adults with a recent history of falls (**Chapter 5**). Conclusively, in an analysis of the short-term (one week post-intervention) results of our RCT, we found that participation in a PBT program including multiple perturbation types and directions did not lead to additional effects to usual care on balance control measured with the Mini Balance

Evaluation Systems Test (Mini-BESTest) or fear of falling measured with the Falls Efficacy Scale International (FES-I) in community-dwelling older adults with a recent history of falls (**Chapter 6**).

Discussion of main findings

In this part of the discussion, we will reflect on our main findings in relation to the findings in this thesis and the recent literature.

PBT to reduce falls in older adults

One of the aims of this thesis was to further our understanding on the effectiveness of PBT to prevent daily-life falls in older adults. The results of our systematic review showed reductions in daily-life falls and/or injurious falls after PBT in older adults with and without neurological conditions (**Chapter 2**). These results indicate that PBT may be an effective intervention to reduce daily-life falls in older adults. Our findings are in line with those of a recently updated systematic review and meta-analysis by Devasahayam *et al*. (2022) of 25 studies in older adults and individuals at increased risk of falls.[1] This review found that participants in reactive balance training were less likely to fall compared to control groups (fall risk ratio 0.75, 95% confidence interval 0.60-0.92, P=0.006).[1] Looking specifically at studies evaluating the effects of PBT in comparison to a control group on daily-life falls in community-dwelling older adults, we are aware of three new studies that have been published since the publication of our systematic review. In 2020, Lurie *et al*. published the results of a pragmatic RCT, comparing the additive effects of PBT (treadmill accelerations or decelerations during standing and walking) in addition to usual gait/balance training in older adults referred to physiotherapy for gait or balance training.[2] At 3 months follow-up, they found a significantly reduced risk of fall-related injuries (relative risk 0.43), and a non-significant reduction in the risk of any fall (relative risk 0.78) in comparison to usual care alone. Rogers *et al*. (2021), compared the effects of PBT (lateral waist-pull perturbations) to a control group receiving flexibility/relaxation exercises in healthy community-dwelling older adults.[3] Their results revealed a non-significant reduction in falls in the PBT group (relative risk 0.44) compared to the control group. Wang *et al*. (2022), studied the effects of a single session of 40 treadmill slip-perturbations compared to unperturbed treadmill walking in community-dwelling older adults.[4] No significant between-group difference in daily-life falls during a 6 month follow-up period was demonstrated. This is a surprising contrast to an earlier study by Pai *et al*. (2014), where a similar training dose (24 overground slip-perturbations) yielded significant reductions in daily-life falls up to 12 months after the intervention.[5] The mixed results of evidence-based interventions such as those described above indicate that there is still much to be learned about the development of optimal PBT protocols.

Application of PBT protocols in clinical practice

Based on our findings in **Chapter 2**, we developed and applied a PBT-protocol, and in **Chapter 6** we compared the additional effects of this training to usual care. The primary outcome measure in this study was (reactive) balance control measured with the Mini-BESTest. Although the results of this study showed a trend towards improved balance control in both groups, the effect of PBT in addition to usual care was not statistically different from usual care alone. We concluded that our PBT protocol was not superior in addition to usual care for improving balance control (**Chapter 6**). The results of this study contrast with the beneficial effects of PBT reported in the literature predating this thesis. In this section, we will reflect on the different factors that should be considered in the development of PBT protocols for clinical practice, as described in **Chapters 2 and 5**. In light of the mixed findings in this thesis and the recent literature, we will discuss if these factors may or may not have contributed to these contrasting findings and need to be reconsidered in future development of PBT protocols.

Treadmill-based setups and therapist-applied perturbations seem to be the most practical setups for clinical practice (**Chapter 2**). Given the low cost and limited equipment required, therapist-applied perturbations could be considered the most feasible type of perturbations. In comparison to other setups, treadmill-based setups are also still relatively low cost and require little space. As falls in daily life tend to occur during execution of movement, treadmill-based setups can be considered more task-specific as perturbations can be applied during walking.[6,7] Additionally, the mechanical perturbations applied through treadmill-based systems provide greater control over perturbation magnitude and timing compared to therapist-applied perturbations. While walkway/overground setups may have higher ecological validity in terms of context, unpredictability of perturbation timing and consequently reliance on reactive balance control strategies may be higher using treadmill-based setups.[7,8] In **Chapter 5**, we evaluated the acceptability of our PBT protocol, in which we used the Computer Assisted Rehabilitation Environment (CAREN), an advanced system including a dual-belt treadmill embedded in a motion platform. We found that participants overall were positive about their experience with the technology used during training, and some participants specifically described that the treadmill perturbations felt like a good simulation of how falls can happen in daily life. Treadmill-based systems still seem a feasible and suitable set-up for the clinical application of PBT, and it is not surprising that they are still a widely used setup in recent PBT studies in older adults.[2,4,7,9,10]

Multidirectional perturbations that target several balance recovery strategies might be the most advantageous for falls reduction in older adults (**Chapter 2**). We found that studies included in our systematic review all included perturbations in the anteroposterior direction, inducing either only a backward or forward balance loss, or a combination of both. While this may result in improvements in balance recovery for that specific direction, these improvements may not transfer to and benefit reactive balance control in other directions.[11,12] As balance loss in daily life can occur in numerous ways, it is important to consider how training adaptations can be optimized to benefit daily life situations. For example, it should be considered that also balance recovery in the mediolateral direction seems to be decreased in older adults, in reaction to a mediolateral perturbation[13] as well as after compensatory forward stepping.[14,15] To address this issue, we included a range of perturbation types and directions in our training protocol. This approach was also proposed in a recent study as a viable approach to ensure ecological validity to the unpredictable nature of perturbations in daily life, as well as address the proposed directional specificity of training-induced adaptations.[16] From this viewpoint, the application of multidirectional perturbations still seems a favorable choice to promote generalizability of training effects to daily-life falls in older adults. However, in our RCT we used this approach and did not find a significant additional effect of PBT on (reactive) balance control measured with the Mini-BESTest. More research is needed to determine how increased variation in perturbation types affects the generalizability of PBT effects, and how much variation is optimal to impact balance control and daily-life falls in older adults.

Selecting perturbation magnitudes that are safe and tolerable while still challenging for the participant appears to be a reasonable choice in clinical applications (**Chapter 2**). High-magnitude perturbations, initially causing participants to require support from the safety harness to regain stability, appear to trigger fast and significant adaptations in balance recovery behavior that can be retained long-term.[5,17-19] However, safety, tolerability and acceptability of these perturbations in older adults or patient groups should be considered. If the required training dose exceeds the tolerance threshold of participants, this may lead to inability to physically cope with the perturbations or anxiety during training.[8] Anxiety has been found to limit acceptability and increase drop-out rates in PBT.[20] Additionally, anxiety may negatively affect reactive balance control (resulting in more rigid and delayed responses) during training.[21,22] One method that has been proposed to increase training tolerance and mitigate anxiety is to progressively increase perturbation intensity (e.g. perturbation magnitude or unexpectedness) based on the individual participant's abilities.[8,16] We adopted this method in our PBT protocol and found that this was a facilitating factor in both reducing the perceived intervention burden and increasing acceptability to participants (**Chapter 5**). PBT protocols with progressive perturbation intensity have yielded significant improvements in reactive balance control, laboratory-induced falls and injurious falls in older adults.[2,23,24] However, while it seems plausible that this approach may cause a rightward shift in the learning curve, the impact of perturbation magnitude on motor learning and retention is not yet clear.[8] Based on our findings and recent literature, applying perturbations of progressive magnitude and/or unpredictability remains a useful strategy to mitigate anxiety and increase tolerability, but more research is needed to determine the impact of this strategy on the required training dose.

The training dose-response relationship is a critical factor that should be considered for the clinical applicability of PBT. In contrast to conventional balance training, PBT studies have shown long-lasting beneficial effects on balance recovery responses[17,19] and daily-life falls[5] after a single training session. While these results are promising, we found that little was known about the optimal dose of PBT at the time of our review, which may have contributed to the highly heterogeneous training doses we found in the included studies. Accounting for a potential effect of the progressive perturbation approach and multiple perturbation types we applied in our PBT protocol, we increased our training dose to three sessions (**Chapter 4**). Still, the dose-response relationship of PBT remains an important research gap today. In a recent study, Karamanidis *et al*. (2020) provided a thorough discussion of the available literature on the dose-response relationship of PBT in older adults.[8] Based on the available literature, they suggest that healthy older adults can demonstrate reactive balance adaptations (measured with MoS or success of balance recovery) after only 4-5 repeated perturbations[18,25], and that middle-aged older adults can retain adaptations over several months after being exposed to 8 repeated gait-trip perturbations.[26] Moreover, based on studies in younger and older adults they suggest that the generalizability of treadmill perturbation training effects (to overground perturbations) seems to improve with higher practice dose[27-29], where one study in older adults found evidence of a possible dose threshold (plateau effect) at 24 perturbations in healthy older adults.[27] While these studies provide valuable first insights in the dose-response relationship of PBT, it should be noted that they all applied a single perturbation type and magnitude in each study and included healthy adults with no known increased risk of falls. For clinical application, it seems plausible that the dose-response relationship is not static, but rather affected by factors related to training characteristics and the intended population such as those discussed in the previous paragraphs. For example, low physical tolerability or anxiety may be mitigated by applying progressive perturbation magnitudes instead of starting off at a very high magnitude[6], but this adjustment may affect the required training dose. Comparably, while including multiple perturbation types and directions may be required to ensure meaningful generalizability to daily life[6,16], reaching a minimal dose threshold for each perturbation type will inevitably increase the total required training dose. Another factor that should be considered when selecting the training dose is the intended training population. Studies have found that while adaptations to repeated perturbations can be achieved in individuals with neurological disorders, these adaptations appear to occur after more repetitions and with more variability than in healthy controls[26,30-32], summarized in Karamanidis *et al*.,[8] In **Chapter 2**, studies showing significant reductions in daily-life falls in people with Parkinson's disease administered markedly higher training doses compared to studies including healthy older adults.[6] Interestingly, our results in **Chapter 3** also indicated better and more uniform adaptations to repeated perturbations in older adults without, compared to those with a recent history of falls. As none of these older adults were diagnosed with any neurological disorder, these findings might hint that the required training dose may also be affected by other population characteristics. Considering these factors, the training dose may be a possible explanation for the lack of significant additional effects on balance control found in **Chapter 6**. The dose-response relationship of PBT is an important remaining research gap that requires further study.[33] While recent studies have provided valuable first insights, factors such as clinical applicability and the intended population of training should be considered in future studies.

Generalizability of training adaptations to other tasks or contexts is a highly desirable effect in the clinical application of PBT.[34] To have a beneficial impact on daily life, it is essential that in the development of PBT protocols, not only direct adaptations but also generalizability to other tasks and contexts are considered.[8] Thus, task-specificity may simultaneously be an advantage and a challenge in PBT. As described in **Chapter 6** in this thesis, studies have found positive results for generalization of training adaptations to situations with some degree of similarity (e.g., the same perturbation type in a different context such as from treadmill-slip to overground slip perturbations[35,36], or interlimb transfer in the same context and perturbation type[37]). In contrast, recent studies by Song *et al*. and König *et al*. did not find significant transfer of training adaptations from treadmill trip-like perturbations to the seemingly similar tasks of balance recovery to an overground gait trip perturbation or a forward lean-and-release perturbation from stance.[38,39] König *et al*. (2022) hypothesized that despite the apparent similarity of both tasks, they may differ in critical task parameters (such as sensory input or muscle activity patterns) that could result in different neuromotor control of responses.[40] Using the muscle synergy concept to compare the responses to both types of perturbations, they found clear differences in both timing and function of the recruited muscles. Their results indicate that differences in muscle synergies between perturbation recovery responses might be a limiting factor to transfer of adaptations.[40] Similarly, two studies by Wang *et al*. and Pai *et al*. showed surprisingly contrasting results: in otherwise very similar studies, a significant reduction of daily-life falls in older adults was found after 24 overground slip-perturbations, but not after 40 treadmill slip-perturbations.[4,5] Combined, the results of these studies indicate that kinematic task-specificity might play a bigger role in the generalizability of PBT effects than was first expected, which may need to be considered in future studies. The relevance of these results to the findings in this thesis are two-fold. First, while requiring a seemingly similar balance recovery reaction, there may be differences in muscle synergies between the perturbation types included in our PBT protocol and the lean-and-release perturbations incorporated in the Mini-BESTest. These differences might explain the contrast between the subjectively experienced progression during training and the lack of significant additional effects on Mini-BESTest scores. Second, these findings may further emphasize the importance of optimizing the similarity between training and real-life situations, such as applying unexpected and multidirectional perturbations during walking as proposed in **Chapter 2**.

Even the most effective interventions are likely to fail if they are not acceptable to the target population. Acceptable interventions are more likely to yield high adherence rates[41], which in turn may result in a better effectiveness of the intervention.[42] In contrast, low acceptability, for example due to training-related anxiety, may increase drop-out rates and thus limit the effectiveness of PBT.[20] In **Chapter 5**, we concluded that PBT is perceived acceptable by older adults with a history of falls. Moreover, the results of this study provide important insights in the development of more optimized training protocols. For example, most participants did not experience anxiety during the training sessions. For those participants that did, the use of a safety harness, guidance by the trainer, and gaining experience with the training were described as factors facilitating the decrease of anxiety. This last factor may underwrite the benefit of gradually progressing perturbation intensity, allowing participants to first gain some experience with PBT. The personalized progression of the training was also mentioned as a facilitating factor decreasing the burden of the training. However, participants were less positive about the numeric rating scale (NRS) score we used as a tool for this personalization, which was not very intuitive. Thus, in future programs, other strategies to personalize training progression might be considered. Participants described that the novelty of the training and technology (including the virtual environments) contributed to their enjoyment of the training, which was identified as a facilitating factor. An important consideration in the development of PBT programs may be how to keep motivation/arousal optimal to facilitate learning.[16] This may be achieved by individualizing training to keep the challenge appropriate, and by finding ways to make the training fun, for example by using virtual training environments.[16,43] Lastly, while PBT in its essence is an individual training paradigm, some participants indicated that they would value to see how others performed during the training sessions or to share fall-related experiences with peers. As promoting the social value of falls prevention interventions has been previously identified as a facilitator, facilitating contact between participants may be considered in future PBT programs.[44]

Methodological considerations

For informed interpretation of the results of this thesis, it is important to consider the choices that were made in the design phase and their impact. While most methodological considerations have been discussed in the individual chapters, two overarching themes are discussed below.

Outcome measures

Our overall objective in this thesis was to learn more about the effectiveness and applicability of PBT for community-dwelling older adults. This objective emerges from the proliferating evidence that PBT is a promising intervention for falls prevention in this population. As such, the gold standard outcome would be to measure prospective falls in daily life. Thus, in our systematic review (**Chapter 2**), we only included intervention studies that measured effects of PBT on this outcome. But as falls don't occur with high frequency in community-dwelling older adults, the high required sample size to accurately measure prospective falls as a primary outcome was unachievable within the practical limits of this project. Therefore, we decided to use another primary outcome measure in our RCT, and included daily-life falls as a secondary outcome. While the results on prospective falls were not included in this thesis due to time constraints, a preliminary analysis has since shown a lower rate of fallers during the 6 months follow-up in the PBT group compared to the control group. As the primary outcome in our RCT, we were interested in the differential effects between both treatment groups on (reactive) balance control. We selected an outcome measure that included a perturbation type that was novel to both groups, and could be measured outside of the movement lab. The choice for the Mini-BESTest was then made because this is a comprehensive balance test with good reliability and validity, that specifically includes reactive balance control, and has a significantly smaller ceiling effect in community-dwelling older adults compared to the Berg Balance Scale.[45,46] Additionally, this test requires little resources and can be applied by every physiotherapist. However, we found that our study population, despite one or more recent falls causing them to require treatment at the hospital outpatient clinic, already showed high scores on the Mini-BESTest at baseline (median total score 23 out of 28 points, median reactive balance sub-score 4 out of 6 points in the PBT group). Additionally, as discussed above, new studies indicate that more similarity between perturbation types may be required for optimal generalization of adaptations than was first expected. Combined, these factors indicate that the suitability of the Mini-BESTest as an outcome measure for the effectiveness of PBT in community-dwelling older adults may need to be reconsidered. Further research is required to determine which outcome measures besides daily-life falls may be most suitable for this purpose. For example, one possible alternative that has been suggested is measurement of near falls with wearables.[47]

Study population and generalizability

Our objective was to include a study population of community-dwelling older adults at increased risk for falling. As having experienced a previous fall is an important prognostic risk factor for future falls (OR 2.8 after a single fall, OR 3.5 after recurrent falls), we used this as one of the inclusion criteria in our experimental studies.[48-50]

Further in- and exclusion criteria were applied, for example to ensure safety of training (e.g. being able to walk unassisted for 15 minutes, absence of osteoporosis or relevant recent fractures). In the interpretation of our study results, it should be considered that the controlled nature of these studies inevitably impacted on their external generalizability, for example to older adults who are unable to walk on a treadmill for 15 minutes. However, a substantial decline in reactive balance control can already be present in these independently walking community-dwelling older adults, which will not become evident until a slip or a trip occurs.[51] As these older adults may not always be recognized as persons at increased risk for falling based on commonly used risk factors, this may be an important population that can benefit specifically from PBT. Previous studies have shown that PBT can reduce falls in daily life by up to 50% in healthy community-dwelling older adults.[5,52,53]

Future research directions

Based on the results presented in this thesis, multiple directions for future research can be formulated. The contrasting results found in our and other recent studies compared to the literature predating this thesis, highlight the need to learn more about the mechanisms underlying effective PBT. *How*, and with *which dose*, do we need to train older adults to have a *meaningful effect on falls* in daily-life? Firstly, as daily-life falls are the gold standard outcome measure, studies should aim to either include a sufficient sample size, or to measure falls as a secondary outcome measure. However, as the required sample size to measure daily-life falls with sufficient statistical power is not always achievable, it would be useful to determine or develop a measure that can serve as a proxy for daily-life falls. This proxy measure could allow for smaller sample sizes in the current phase of PBT research, while still giving an essential indication of training effects on a meaningful outcome that can be compared to a control group. Secondly, important and related research gaps remain in the directions of training dose-response relationship and generalizability. On the one hand, generalizability of perturbation-induced adaptations may be limited; on the other hand, it seems plausible that including more perturbation types or directions will impact the required training dose. Thus, future studies may focus on the most prevalent circumstances of falls in a certain population to derive a focused set of perturbations for training, and subsequently investigate the required training dose based on these training contents. Thirdly, to enhance applicability of PBT in clinical settings, future studies may particularly want to focus on clinically feasible and acceptable PBT-setups, such as treadmill-based systems.

Conclusions

This thesis resulted in an improved understanding of the effectiveness and applicability of perturbation-based balance training for community-dwelling older adults, knowledge which could underpin the implementation of PBT in clinical practice. The findings of our

RCT showed no superior effects of PBT in addition to usual care on (reactive) balance control. However, in our systematic review we did see significant reductions in daily-life falls in community-dwelling older adults with and without neurological disorders in clinical practice after PBT. Although the PBT literature predating this thesis provided some indications of feasibility and acceptability, our review and qualitative study present the first in-depth explorations of this topic in older adults and provide important insights for future development and implementation of PBT interventions. In synthesis with mixed results in other recent studies, the results in this thesis highlight the need for further research to elucidate the mechanisms underlying effective PBT, how to best measure PBT effects, and how this intervention can be successfully applied for each target population. The findings in this thesis provide important insights in the effectiveness and applicability of PBT in community-dwelling older adults and offer starting points for future research and implementation.

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Impact paragraph

Annually, approximately one in three adults aged 65 years and older, and 50% of adults above the age of 80 years, experience a fall.[1] Falls are the leading cause of injuries and injury related death in older adults and present not only a substantial threat to health, but also to wellbeing. In 2020, every 5 minutes an older adult visited the emergency department due to a fall incident.[2] As our population is ageing, the need for effective and efficient falls prevention interventions increases. Therefore, this thesis was centered around a promising new intervention for falls prevention in older adults: perturbation-based balance training (PBT).

Effectiveness of PBT for older adults

From our literature review, we concluded that PBT seems a feasible and effective approach to prevent daily-life falls in older adults with and without neurological conditions. However, in our own study we did not find a meaningful additional effect of PBT to usual care physiotherapy on balance control. In combination with mixed findings from other recent studies, this indicates that more research is needed to determine whether PBT can be effective for falls prevention in older adults, especially in a way that can be implemented in clinical practice. Based on this evidence, it would be premature to advise physiotherapists to purchase (costly) equipment to provide PBT in their clinical practice. If physiotherapists already have equipment and apply PBT in their clinical practice, it would be useful to systematically document and report their data, as this information may be helpful in the further development and implementation of PBT interventions.

Development and implementation of PBT protocols

The results of our literature review and interviews provide important insights for the further development and implementation of PBT interventions for older adults. Even effective interventions are likely to fail if they are not acceptable to the target population. It was found that being able to feel safe during training, as well as the perceived impact of increased self-efficacy and balance confidence were facilitating factors for the acceptability of PBT. Moreover, participants who experienced initial apprehension or anxiety during training described that the gradual progression of the training difficulty was a facilitating factor for mitigating this anxiety. Thus, we recommend that these factors are considered in the development of future PBT interventions. Conversely, a new theme also emerged from the interviews. Some participants described challenges regarding the training setting, such as having a preference for a social aspect to training (e.g. group training) and having difficulties in travelling to the training location. Knowing about these potential barriers can also help in the development of future interventions, enhancing their effectiveness through improving acceptability. Moreover, these findings can be combined with factors that should be considered in the design of PBT protocols as identified in our literature review (e.g., perturbation characteristics such as magnitude). For example, gradual progression of perturbation magnitude can be considered as a strategy to mitigate anxiety during training.

Falls prevention? Not for me.

We found that including participants for our study proved challenging, despite the fact that we approached older adults who had recently visited our hospital's outpatient clinic due to a fall incident. From the potentially eligible older adults that were approached, approximately half of them declined to participate in the study. Older adults quite often mentioned reasons like i) they did not view themselves as someone who needed balance training or falls prevention, despite having recently fallen one or multiple times or ii) the burden of participating in the study and training was too high (mostly in combination with (care for) comorbidities or in terms of time). We found that these drops in inclusion rates and reasons not to participate were comparable to those of falls prevention in general.[3,4] Additionally, in interviews with older adults who had participated in our PBT program we found that they had little prior knowledge about falls prevention, and those who had thought about it were unsure of who to approach about the topic or if it could be beneficial for them. However, these older adults generally described that they would consider anything they could do to prevent future fall incidents as valuable. These findings highlight that there is still a need to improve communication to inform older adults not only about the possible consequences of falls, but also specifically about how falls prevention can potentially benefit them. For example, involving older adults in the planning of how to promote an intervention can provide better insight in their perspective.

Sharing science

While the theoretical development of PBT interventions at this point may be focused in science, in the end they are specifically developed for the benefit of older adults, physiotherapists and medical practitioners. It is important to disseminate our findings in ways that are accessible by anyone who may be interested. Therefore, all studies in this thesis have been published under open-access licenses in scientific peer-reviewed journals, and have been presented and discussed at a number of national and international conferences aimed at researchers and health professionals. Additionally, summaries of our work will be published in trade journals and local news items, to enhance knowledge translation to health professionals without a scientific background and the general public.

Concluding remark

Given the substantial burden of falls on individuals and society, it is essential to evaluate promising new interventions. While PBT is a promising intervention for falls prevention, the results of this thesis highlight the challenge of applying PBT in a way that optimizes effectiveness as well as feasibility and acceptability in clinical practice. The findings of this thesis provide important insights that can offer starting points to address this challenge for future research and implementation.

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Summary

Falls present a substantial threat to the health and wellbeing of older adults. The ageing of the population presents an increasing need for effective and efficient falls prevention interventions. The incidence and consequences of falls are introduced in **Chapter 1**, alongside a description of falls prevention through balance training in general, and more specifically about perturbation-based balance training (PBT). Lastly, this chapter presents the outline of this thesis.

Balance training is a form of exercise intervention that has been found to be particularly effective in reducing fall risk in older adults. Balance is a multidimensional concept; for example, strategies to achieve, maintain or restore balance can be proactive (when the movement is anticipated), or reactive (when the movement is unexpected or needs to be adjusted). In most balance interventions to date, exercises are mostly focused on training proactive or predictive balance control, and less on reactive balance control. However, many falls in older adults (approximately 59% in community-dwelling older adults) are caused by unexpected perturbations during walking, such as slips or trips, and require a reactive balance recovery strategy. In recent years, there has been an increasing interest in interventions that are more task-specific to the recovery reactions required to prevent a fall.

Perturbation-based balance training (PBT) is such a task-specific intervention, that aims to improve reactive balance control after destabilizing perturbations in a safe and controlled environment. During PBT, participants are exposed to unexpected balance perturbations such as slips or trips, during various activities of daily living such as standing or walking. While recovery from a novel perturbation seems to be less effective in older adults compared to young adults, their capacity to adapt and improve reactive balance with training seems intact. There is a growing body of evidence for the effectiveness of PBT, with studies showing direct balance adaptations during training, as well as retention of these adaptations, and improvements in other measures of balance control. Moreover, studies have found meaningful and significant reductions in daily-life falls in older adults, even after very brief periods of training.

Despite the growing interest in PBT in research, there has been little transfer of PBT to clinical practice. Given the substantial burden of falls on individuals and society, it is essential to evaluate if promising new interventions such as PBT may be feasible and effective for application in clinical practice. Therefore, the aim of this thesis is to further our understanding of the effectiveness and applicability of this relatively new intervention in clinical practice, with the perspective that this knowledge could further the readiness of PBT for implementation in clinical practice.

Chapter 2 describes a systematic review of studies on the effectiveness of PBT to reduce falls in older adults, in which factors that should be considered for application of PBT in clinical practice are synthesized and discussed. A total of eight studies are included in this review, each comparing the effects of PBT versus a control group on falls in the everyday life of older adults. These studies show a significant reduction of falls incidence among healthy older adults and certain patient groups (e.g. people with Parkinson's disease and stroke), and clinically relevant reductions of falls in more frail older adults. Looking at factors that should be considered in the application of PBT in clinical practice, the most practical methods for application in clinical settings might be treadmill-based systems and therapist applied perturbations. Moreover, PBT that incorporates multiple perturbation types and directions might be of most benefit. Based on these findings, PBT appears to be a feasible and effective approach to falls reduction among older adults in clinical settings.

Chapter 3 explores the extent to which unperturbed walking variability, stability following a novel perturbation and adaptability to repeated perturbations relate to falls history in older adults. As falls most commonly occur during walking due to unexpected balance perturbations, walking-based balance assessment including walking stability and adaptability to such perturbations could be beneficial for fall risk assessment in older adults. This cross-sectional study compares data from community-dwelling older adults with and without a history of falls that completed a series of unperturbed and perturbed walking trials. No significant differences were found in unperturbed walking parameters or their variability. Overall perturbation-recovery step behavior differed slightly (not statistically significant) between groups after the first perturbation, where the group with a history of falls showed slightly delayed and more inconsistent recovery responses. These differences became more pronounced and significant after repetition of perturbations, and the group without a history of falls significantly reduced the number of recovery steps needed across the trials, whereas the group with a history of falls did not. Older adults without a history of falls demonstrated more signs of adaptability to repeated perturbations. Adaptability may give a broader indication of the ability of the locomotor system to respond and improve responses to sudden walking perturbations than unperturbed walking variability or recovery to a single novel perturbation. Adaptability may thus be a more useful marker of falls history in older adults, but may also have implications for the required training dose in older adults with a history of falls, and should be considered in further research.

Chapter 4 describes how the lessons learned from the systematic review in Chapter 2 are applied to the setting of the MUMC+ in the design of a PBT protocol. This study protocol describes how community-dwelling older adults who presented at the MUMC+ outpatient clinic after a fall incident will be included and randomized to receive usual care (physiotherapy referral) with or without the addition of PBT. A PBT intervention is designed consisting of three 30-minute training sessions including multiple perturbation types and directions applied during standing and treadmill walking on the Computer Assisted Rehabilitation Environment (CAREN) system. The training content and duration is standardized, while training progression is individualized based on each participant's balance abilities. The protocol includes two quantitative outcome measures which are measured at one week and three months post-intervention; balance control measured with the Mini Balance Evaluation Systems Test (Mini-BESTest), and fear of falling measured with the Falls Efficacy Scale International (FES-I). Additionally, daily-life falls will be monitored for six months using falls calendars. To evaluate the acceptability of the PBT protocol for older adults, a qualitative study is embedded in the protocol of this randomized controlled trial (RCT).

Chapter 5 reports on this qualitative study with the aim of evaluating the acceptability of PBT in community-dwelling older adults with a recent history of falls. This study includes a representative subsample of 16 older adults who completed the PBT intervention as part of our RCT. The acceptability of the training protocol is discussed using semi-structured interviews based on the Theoretical Framework of Acceptability (TFA). The results indicate that this PBT protocol is perceived as acceptable by older adults with a recent history of falls, and highlight key areas for potential future modifications. Enjoyment of the novel training and technology, being able to feel safe during training, and perceived impact of increased self-efficacy and balance confidence are identified as facilitating factors. Potential issues include initial apprehension or anxiety during training and perceived impact being predominantly psychological instead of physical. Complementary to the TFA one additional theme emerged which describes challenges regarding the training setting for some participants, such as preference for group training and difficulty travelling to the training location.

The short-term results (1 week post-intervention) of our RCT are presented in **Chapter 6.** In this study, 82 community-dwelling older adults are included, receiving usual care with (n = 39) or without the addition of three 30-minute sessions of PBT. Balance control measured with the Mini-BESTest shows a trend towards improvement in both groups, but changes are not significantly different between groups. Falls efficacy measured with the FES-I did not change in either group. Participation in a PBT program including multiple perturbation types and directions did not lead to significant additional effects to usual care on balance control or fear of falling in community-dwelling older adults with a recent history of falls.

Chapter 7 provides a reflection on the main study findings of this thesis in relation to recent literature, discusses methodological considerations and makes suggestions for future research. This thesis resulted in an improved understanding of the effectiveness and applicability of PBT for community-dwelling older adults, knowledge which could underpin the implementation of PBT in clinical practice. The findings of our RCT and systematic review showed mixed results on the effectiveness of PBT in older adults. Although the PBT literature predating this thesis provided some indications of feasibility and acceptability, our review and qualitative study present the first in-depth explorations of this topic in older adults and provide important insights for future development and implementation of PBT interventions. In synthesis with mixed results in other recent studies, the results in this thesis highlight the need for further research to elucidate the mechanisms underlying effective PBT, how to best measure PBT effects, and how this intervention can be successfully applied for each target population. The findings in this thesis provide important insights in the effectiveness and applicability of PBT in community-dwelling older adults and offer starting points for future research and implementation.

Samenvatting

Valincidenten vormen een aanzienlijke bedreiging voor de gezondheid en het welbevinden van ouderen. De vergrijzing van de bevolking zorgt voor een toenemende behoefte aan effectieve en efficiënte valpreventie. Een beschrijving van incidentie en gevolgen van valincidenten wordt geïntroduceerd in **hoofdstuk 1**, evenals een beschrijving van valpreventie door middel van balanstraining in het algemeen, en specifiek met behulp van perturbatietraining (PBT). Tot slot wordt in dit hoofdstuk een overzicht van de hoofdlijnen van dit proefschrift gepresenteerd.

Balanstraining is een vorm van oefentherapie die in voorgaand onderzoek bijzonder effectief is bevonden voor het verminderen van valrisico bij ouderen. Balans is een multidimensionaal concept; strategieën voor het verkrijgen, behouden of herstellen van balans kunnen bijvoorbeeld proactief zijn (als de beweging wordt verwacht), of reactief (wanneer een beweging onverwacht is of moet worden bijgesteld). Tot op heden zijn de meeste interventies met balanstraining voornamelijk gericht op het trainen van proactieve balanscontrole, en minder op reactieve balanscontrole. Echter, een groot deel van de valincidenten bij ouderen (ongeveer 59% bij zelfstandig wonende ouderen) zijn het gevolg van onverwachte balansverstoringen tijdens het lopen, zoals struikelen of uitglijden, en vereisen dus een reactieve strategie van balansherstel. In de afgelopen jaren is er steeds meer interesse ontstaan in interventies die taak-specifieker zijn voor de herstelreacties die nodig zijn om een valincident te voorkomen.

Perturbatietraining (PBT) is zo'n taak-specifieke interventie, die als doel heeft om de reactieve balanscontrole na balansverstoringen te verbeteren door dit te trainen in een veilige en gecontroleerde omgeving. Tijdens PBT worden deelnemers blootgesteld aan onverwachte balansverstoringen zoals struikelingen of uitglijden tijdens het uitvoeren van verschillende dagelijkse activiteiten zoals staan of lopen. Er is steeds meer bewijs voor de effectiviteit van PBT, met studies die directe adaptaties van de balans tijdens training, evenals behoud van deze adaptaties en verbeteringen in andere maten van balanscontrole aantonen. Bovendien vonden studies ook relevante en significante verminderingen van valincidenten in het dagelijks leven, zelfs na relatief korte trainingsperiodes.

Ondanks de toenemende interesse in PBT op onderzoeksgebied, wordt PBT nog weinig toegepast in de praktijk. Gezien de aanzienlijke gevolgen van valincidenten voor individuen en de maatschappij, is het essentieel om te evalueren of veelbelovende nieuwe interventies zoals PBT uitvoerbaar en effectief zijn voor toepassing in de praktijk.

Hoofdstuk 2 beschrijft een systematische literatuurstudie van onderzoeken naar de effectiviteit van PBT ter valpreventie voor ouderen, waarbij factoren worden besproken die moeten worden overwogen voor de toepassing van PBT in de praktijk. In totaal zijn acht onderzoeken opgenomen in deze literatuurstudie, die allemaal het effect van PBT op valincidenten in het dagelijks leven van ouderen vergelijken met een controlegroep. Deze studies tonen een significante vermindering van de valincidentie aan bij gezonde ouderen en bepaalde patiëntenpopulaties (bijvoorbeeld mensen met Parkinson of die een beroerte hebben doorgemaakt), en een klinisch relevante vermindering van het aantal valincidenten bij kwetsbare ouderen. Met het oog op factoren die moeten worden overwogen voor de praktische toepassing van PBT, lijken trainingssystemen met een loopband of manuele perturbaties het meest toepasbaar. Bovendien levert PBT waarbij meerdere types en richtingen van perturbaties worden toegepast mogelijk het meeste voordeel op. Op basis van deze bevindingen lijkt PBT een toepasbare en effectieve benadering voor de praktijk om valincidenten bij ouderen te verminderen.

Hoofdstuk 3 verkent in hoeverre i) variabiliteit in het looppatroon, ii) stabiliteit na een onverwachte balansverstoring en iii) aanpassingsvermogen op herhaalde balansverstoringen gerelateerd zijn aan de valgeschiedenis van ouderen. Aangezien valincidenten vaak het gevolg zijn van onverwachte balansverstoringen tijdens het lopen, is het plausibel dat een analyse van balans tijdens het lopen van toegevoegde waarde zou kunnen zijn voor het in kaart brengen van valrisico bij ouderen. Deze dwarsdoorsnede studie vergelijkt data van zelfstandig wonende ouderen met- en zonder valgeschiedenis die looptesten met- en zonder balansverstoringen hebben uitgevoerd. De resultaten tonen geen significante verschillen in gangparameters tijdens onverstoord lopen. Het globale herstelpatroon na een balansverstoring verschilt licht (niet statistisch significant) tussen de groepen na de eerste balansverstoring, waarbij de groep met een valgeschiedenis licht vertraagde en minder consistente herstelreacties laat zien. Deze verschillen worden duidelijker en statistisch significant na herhaalde balansverstoringen. De groep zonder valgeschiedenis vermindert significant het aantal benodigde stappen om te herstellen bij herhaling, terwijl dit niet gebeurt bij de groep met valgeschiedenis. Ouderen zonder valgeschiedenis laten meer tekenen zien van aanpassingsvermogen op herhaalde balansverstoringen. Aanpassingsvermogen geeft mogelijk een breder beeld van het vermogen van het bewegingsapparaat om te reageren en om herstelreacties te verbeteren na een balansverstoring dan het gangpatroon tijdens onverstoord lopen of het herstel na een enkele onverwachte balansverstoring. Aanpassingsvermogen is dus mogelijk een meer bruikbare indicator van valgeschiedenis bij ouderen, maar heeft mogelijk ook implicaties voor de benodigde trainingsdosis voor ouderen met een valgeschiedenis, en zou moeten worden overwogen in verder onderzoek.

Hoofdstuk 4 beschrijft hoe de geleerde lessen van de literatuurstudie in hoofdstuk 2 worden toegepast in de setting van het MUMC+ in het ontwerp van een protocol voor perturbatietraining. Dit onderzoeksprotocol beschrijft hoe zelfstandig wonende ouderen die de polikliniek van het MUMC+ bezoeken na een valincident zullen worden geïncludeerd en gerandomiseerd om reguliere zorg te ontvangen (verwijzing voor fysiotherapie), met of zonder de toevoeging van perturbatietraining. Daarnaast beschrijft het protocol de ontwikkelde perturbatietraining, die bestaat uit drie trainingssessies van een half uur waarin meerdere perturbatietypes en perturbatierichtingen worden toegepast tijdens het staan en lopen op het Computer Assisted Rehabilitation Environment (CAREN) systeem. De inhoud en duur van de training wordt gestandaardiseerd, terwijl trainingsprogressie individueel wordt bepaald op basis van het vermogen van de deelnemer om de balans te behouden en herstellen na de balansverstoringen. In het protocol zijn twee kwantitatieve uitkomstmaten opgenomen, die één week en drie maanden na de interventie worden gemeten; balanscontrole gemeten met de Mini Balance Evaluation Systems Test (Mini-BESTest), en valangst gemeten met de Falls Efficacy Scale International (FES-I). Daarnaast zullen valincidenten in het dagelijks leven gedurende zes maanden worden gemonitord met behulp van valkalenders. Om de aanvaardbaarheid van de training voor deelnemers te kunnen evalueren, is er een kwalitatieve studie ingebed in het protocol van deze gerandomiseerde controlestudie (RCT).

Hoofdstuk 5 beschrijft deze kwalitatieve studie, met als doel het evalueren van de aanvaardbaarheid van perturbatietraining voor zelfstandig wonende ouderen met een valgeschiedenis. Een representatieve sub-selectie van 16 ouderen die deelnamen aan de perturbatietraining in de RCT werd geïncludeerd in deze studie. De aanvaarbaarheid van het trainingsprotocol wordt besproken in semigestructureerde interviews gebaseerd op het Theoretisch Raamwerk van Aanvaardbaarheid (TRA). De resultaten tonen aan dat dit perturbatieprotocol als aanvaardbaar wordt ervaren door ouderen met een recente valgeschiedenis, en produceren belangrijke aandachtspunten voor toekomstige aanpassingen. Plezier tijdens deze nieuwe training en met de nieuwe technologie, zich veilig kunnen voelen tijdens de training, en een ervaren effect van toegenomen eigeneffectiviteit en vertrouwen in de eigen balans worden geïdentificeerd als faciliterende factoren. Potentiële knelpunten zijn het ervaren van bezorgdheid of spanning aan het begin van de training, en dat voornamelijk psychologische in plaats van de beoogde fysieke effecten worden ervaren. Een aanvullend thema komt uit de interviews naar voren, waarin sommige deelnemers uitdagingen met betrekking tot de trainingssetting aangeven, zoals een voorkeur voor groepstraining en moeite met reizen naar de trainingslocatie.

De korte termijn resultaten (1 week post-interventie) van onze RCT worden gepresenteerd in **hoofdstuk 6**. In deze studie werden 82 zelfstandig wonende ouderen geïncludeerd, die reguliere zorg ontvingen met (n=39) of zonder (n=43) de toevoeging van drie 30-minuten durende sessies perturbatietraining. Er wordt een positieve trend gezien in balanscontrole gemeten met de Mini-BESTest in beide groepen, maar deze veranderingen zijn niet significant verschillend tussen de groepen. Valangst gemeten met de FES-I veranderde in geen van beide groepen. Deelname aan perturbatietraining met meerdere types en richtingen perturbaties leverde geen significant betere effecten op balanscontrole en valangst op dan reguliere zorg bij ouderen met een recente valgeschiedenis.

In **hoofdstuk 7** wordt gereflecteerd op de belangrijkste bevindingen van de studies in dit proefschrift in relatie tot de literatuur. Daarnaast worden methodologische overwegingen besproken en worden er suggesties gedaan voor vervolgonderzoek. Dit proefschrift resulteerde in een beter begrip van de effectiviteit en toepasbaarheid van perturbatietraining voor zelfstandig wonende ouderen, kennis die de implementatie van perturbatietraining in de praktijk kan onderbouwen. Hoewel de literatuur van voor dit proefschrift enige indicatie gaf van haalbaarheid en aanvaardbaarheid, vormen onze literatuurstudie en kwalitatieve studie de eerste diepgaande verkenning van dit onderwerp bij ouderen, en zorgen deze studies voor belangrijke inzichten voor de verdere ontwikkeling en implementatie van perturbatietraining. In combinatie met de gemengde resultaten van andere recente onderzoeken, benadrukken de resultaten in dit proefschrift het belang van verder onderzoek om meer inzicht te krijgen in de onderliggende mechanismen van PBT, in hoe de resultaten van PBT het best gemeten kunnen worden, en hoe deze interventie succesvol kan worden toegepast voor de verschillende doelgroepen. De resultaten van dit proefschrift geven belangrijke inzichten in de effectiviteit en toepasbaarheid van perturbatietraining bij zelfstandig wonende ouderen, en bieden uitgangspunten voor vervolgonderzoek en implementatie.

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It's a dangerous business, going out your door. You step onto the road, and if you don't keep your feet, there's no knowing where you might be swept off to.
- J.R.R. Tolkien -

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McCrum C, Bhatt TS, **Gerards MHG**, Karamanidis K, Rogers MW, Lord SR, Okubo Y. *Perturbation-based Balance Training: Principles, Mechanisms and Implementation in Clinical Practice*. Front Sports Act Living. 2022 Oct 6;4. doi: 10.3389/ fspor.2022.1015394.

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About the author

Marissa Hubertina Gertruda Gerards was born on May 8th, 1994 in Maastricht, the Netherlands. She completed secondary school at Sophianum College in Gulpen in 2012. The same year she started her bachelor studies in Physiotherapy at Fontys Hogescholen, Eindhoven (BSc. 2015). She started her professional career as a physiotherapist in geriatric rehabilitation at aZM Herstelzorg in Maastricht, which she combined with a part-time master in Human Movement Science at Maastricht University (MSc, 2017). Marissa completed her master's degree with a thesis on dynamic stability in response to gait perturbations in young and older adults.

In 2017, she had the opportunity to combine her interests in research and physiotherapy at the Department of Physiotherapy at Maastricht University Medical Center (MUMC+), where she combined her PhD research with clinical physiotherapy. Her PhD research expanded the work from her master's thesis on the topic of perturbation-based balance training and falls prevention in older adults. Her supervision team consisted of Prof. dr. Ton Lenssen, Prof. dr. Rob de Bie (promotors) and dr. Kenneth Meijer (co-promotor). From 2021, Marissa stopped working as a physiotherapist to combine her PhD research with a research position at the Department of Epidemiology, Care and Public Health Institute, Maastricht University. In 2023, she completed her PhD and continued working as a researcher at the Department of Epidemiology at Maastricht University.