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Comparing the Effects of Two Perturbation-Based Balance Training Paradigms in Fall-Prone Older Adults: A Randomized Controlled Trial

Leon Brüll[a, b, c] Natalie Hezel[a, d] Adamantios Arampatzis[b, c] Michael Schwenk[a, e, f]

[a]Network Aging Research, Heidelberg University, Heidelberg, Germany; [b]Department of Training and Movement Sciences, Humboldt-Universität zu Berlin, Berlin, Germany; [c]Berlin School of Movement Science, Humboldt-Universität zu Berlin, Berlin, Germany; [d]Geriatric Center, Heidelberg University Hospital, Agaplesion Bethanien Hospital Heidelberg, Heidelberg, Germany; [e]Institute of Sports and Sports Sciences, Heidelberg University, Heidelberg, Germany; [f]Department of Sport Science, Human Performance Research Center, University of Konstanz, Konstanz, Germany

Keywords
Perturbation · Balance training · Older adults · Task specificity · Reactive balance

Abstract
Introduction: There is increasing evidence that perturbation-based balance training (PBT) is highly effective in preventing falls at older age. Different PBT paradigms have been presented so far, yet a systematic comparison of PBT approaches with respect to feasibility and effectiveness is missing. Two different paradigms of PBT seem to be promising for clinical implementation: (1) technology-supported training on a perturbation treadmill ($PBT_{treadmill}$); (2) training of dynamic stability mechanisms in the presence of perturbations induced by unstable surfaces ($PBT_{stability}$). This study aimed to compare both program's feasibility and effectiveness in fall-prone older adults. ***Methods:*** In this three-armed randomized controlled trial, seventy-one older adults (74.9 ± 6.0 years) with a verified fall risk were randomly assigned into three groups: $PBT_{treadmill}$ on a motorized treadmill, $PBT_{stability}$ using unstable conditions such as balance pads, and a passive control group (CG). In both intervention groups, participants conducted a 6-week intervention with 3 sessions per week. Effects were assessed in fall risk (Brief-BEST), balance ability (Stepping Threshold Test, center of pressure, limits of stability), leg strength capacity, functional performance (Timed Up and Go Test, Chair-Stand), gait (preferred walking speed), and fear of falling (Short FES-I). ***Results:*** Fifty-one participants completed the study. Training adherence was 91% for $PBT_{treadmill}$ and 87% for $PBT_{stability}$, while no severe adverse events occurred. An analysis of covariance with an intention-to-treat approach revealed statistically significant group effects in favor of $PBT_{stability}$ in the Brief-BEST ($p = 0.009$, $\eta^2 = 0.131$) and the limits of stability ($p = 0.020$, $\eta^2 = 0.110$) and in favor of $PBT_{treadmill}$ in the Stepping Threshold Test ($p < 0.001$, $\eta^2 = 0.395$). The other outcomes demonstrated no significant group effects. ***Conclusion:*** Both training paradigms demonstrated high feasibility and were effective in improving specific motor performances in the fall-prone population and these effects were task specific. $PBT_{treadmill}$ showed higher improvements in reactive balance, which might have been

karger@karger.com
www.karger.com/ger

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Correspondence to:
Michael Schwenk, michael.schwenk@uni-konstanz.de

promoted by the unpredictable nature of the included perturbations and the similarity to the tested surface perturbation paradigm. $PBT_{stability}$ showed more wide-ranging effects on balance ability. Consequently, both paradigms improved fall risk-associated measures. The advantages of both formats should be evaluated in light of individual needs and preferences. Larger studies are needed to investigate the effects of these paradigms on real-life fall rates.

Introduction

Falls in older adults may cause severe physical and psychological consequences and are a burden for the public health system [1]. Modifiable intrinsic fall risk factors are deficits in balance, strength, and gait [2]. Prevention programs based on conventional balance exercises reduced falls by 24% [3]. Twice as high effects (48%) [4] have been reported for task-specific perturbation-based balance training (PBT) programs [5]. While conventional balance training focuses on static and proactive balance, PBT addresses reactive balance to recover from unexpected perturbations [6]. In other words, PBT mimics those everyday scenarios accounting for the majority of falls in community-dwelling older adults, namely, slipping and tripping [7]. Nevertheless, PBT is understudied compared to conventional balance training and has not been widely implemented in fall prevention practice [8].

In particular, it is unclear which PBT paradigms should be transferred into fall prevention practice, both with respect to feasibility and effectiveness. From a feasibility perspective, important elements are safety, adherence, and acceptability in the target population. Transferring PBT into routine care can be challenging given the high task demand including training at the limits of stability (LoS) which may result in anxiety and low adherence [9]. From an effectiveness perspective, the task specificity of PBT for improving reactive balance is important. Different PBT paradigms may produce different results for this specific balance domain. Several PBT paradigms exist including treadmill approaches [10, 11], movable platforms [12], cable-pull systems [13], obstacles [9], and utilizing unstable conditions such as unsteady and uneven surfaces [14].

Out of these concepts, technology-based perturbation treadmill training ($PBT_{treadmill}$) has potential for clinical implementation as it allows training in a safe, controlled environment and the option to mimic unannounced perturbations from multiple directions [11, 15]. However, perturbation treadmills are expensive, hindering routine care transfer. Low-cost, non-tech PBT approaches make use of various kinds of unstable surfaces such as balance pads, BOSU® balls, coordination seesaws, balance cushions, and the Posturomed® to induce instability [16]. This training aims to improve reactive balance control by challenging the mechanisms of dynamic stability, specifically modulation of the base of support and counter-rotations of body segments around the center of mass to compensate for a temporary loss of balance control related to a perturbation [17]. This approach has been shown to improve not only balance recovery performance but also leg strength capacity [14, 16], which is supposed to improve reactive stepping. Therefore, different PBT paradigms exist but these paradigms have not yet been compared systematically.

Previous studies merely compared PBT paradigms with controls lacking PBT [5, 10, 14, 16, 18]. To the best of our knowledge, only one study involved two different PBT paradigms [19]. This cross-over study included a single session with eleven perturbations and found acute stability adaptations in both paradigms, while no transfer of these effects was observed from the treadmill accelerations to the walkway trips in healthy older adults. In general, PBT studies in older adults often focused on healthy individuals [20], while the tolerance to challenging perturbations inducing repeated losses of stability in frail, fall-prone older adults is not clear. From an implementation standpoint, studies should identify those PBT paradigms feasible and effective in key target populations such as fall-prone older adults [21].

Here, we addressed these research deficits by comparing two PBT paradigms in fall-prone older adults (fallen within the previous year and/or a verified fall risk). Specifically, we compared perturbation treadmill training ($PBT_{treadmill}$) (surface translation treadmill paradigm) with the PBT training concept of dynamic stability mechanisms in the presence of perturbations ($PBT_{stability}$) (dynamic stability mechanisms paradigm) [16]. Choosing these two paradigms for comparison seems intuitive due to (a) the promising effects shown in previous studies [14–16], (b) the suggested clinical feasibility, and (c) the high contrast between these programs in terms of utilized devices (perturbation treadmill vs. low-cost training devices). The purpose of this study was to conduct a standardized comparison of $PBT_{treadmill}$ and $PBT_{stability}$ in terms of feasibility and effects against a control group. Therefore, the following hypotheses were investigated: (i) both PBT paradigms are feasible in a fall-prone population, as determined by adherence (>75% attended

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sessions [22]), dropout rate (<20% [23]), and safety (no severe adverse events [SAEs]), (ii) both paradigms are effective in reducing balance-related fall risk, as indicated by at least medium effects ($d > 0.5$) of improvements in the Brief-BEST compared to the control group (CG). Additionally, we explored the impact of both training paradigms on fall risk-related outcomes including different balance domains, functional performance, gait speed, leg strength capacity, and perceived fear of falling to understand potential differences in adaptations to both PBT forms.

Materials and Methods

Study Design

This study was a three armed, parallel grouped, randomized controlled trial at the Institute of Sports and Sports Sciences, Heidelberg University, Germany, approved by the Local Ethics Committee (AZ Schwe 2019/1 2) and pre registered at ClinicalTrials.gov (NCT04087512). Baseline assessments were double blinded. The three study arms included $PBT_{treadmill}$, $PBT_{stability}$, and CG. Due to a shutdown of the institute caused by the COVID 19 pandemic, post assessments had to be canceled for sixteen participants who had completed the full intervention phase (see online suppl. File. 1; for all online suppl. material, see www.karger.com/doi/10.1159/000530167).

Study Population

For recruitment, contact dates of randomly selected age adjusted citizens living in districts adjacent to the study center were provided by the local registration office. The recruitment started in August 2019 and the last post assessment was completed in October 2020. Inclusion criteria were (1) 65 years of age and older, (2) community dwelling or assisted living, (3) ability to walk for at least 20 min without aid, (4) fall prone as defined by having either at least one fall (defined according to Lamb et al. [24]) within the past 12 months or a verified fall risk based on a perceived decrease of balance and poor balance performance measured by the 8 level balance scale (8LBS) (cut off value of 5 points). Participants were excluded if they had (1) severe neurological, orthopedic, cardiovascular, metabolic, or respiratory diseases, (2) uncorrected visual impairments, (3) current chemotherapy, (4) severe vertigo, (5) cognitive impairments (DemTect ≤ 8 points), (6) a body mass index ≥30, or (7) participated in balance training in the previous 3 months. Written consent in accordance with the Declaration of Helsinki was provided.

Study Procedure

After receiving a postal study invitation, interested persons completed a phone based eligibility screening. Eligible participants were in house screened for fall risk (8LBS) and cognition (DemTect) and conducted a treadmill familiarization session including walking for 10 20 min. A few days later, they participated in the baseline assessment, after which the computer generated randomization was conducted (online suppl. File 2). Intervention groups trained for 6 weeks with three sessions per week, while CG received no treatment. Thereafter, the post assessments followed (Fig. 1). The average time between pre and post assessments was of 7.3 ± 0.7 weeks over all groups.

Intervention

Both interventions included 18 training sessions. The duration of active training time per session was similar in both programs to ensure comparability (≈24 min). Both programs set the intensity of the balance tasks close to the individual threshold of stability (i.e., indicated by distinct reactive arm movements or recovery steps). Full details of both programs are provided in a TIDieR checklist (online suppl. File 3). Since no general standard of care training protocol exists to date for PBT, both protocols were based on previous work as stated in the respective descriptions.

Perturbation Treadmill Training

We designed $PBT_{treadmill}$ with the intention to mimic real life fall scenarios requiring reactive balance, considering previous recommendations for implementing PBT in clinical practice [15]. A variety of perturbations were included to increase ecological validity. Different perturbation directions also reduced the predictability of the upcoming perturbation, minimizing proactive adjustments to focus on reactive performance.

The training was individually conducted on a perturbation treadmill (BalanceTutor™, MediTouch LTD, Netanya, Israel) (Fig. 2a), which fulfills the primary factors for successful PBT systems [20]. Participants were secured by a harness adjusted to body height, preventing the knees from touching the ground in case of a fall while still allowing for reactive balance maneuvers.

A detailed training protocol is provided in the supplementary material (online suppl. File 4). The session started with a warm up of 5 min normal walking followed by four perturbation blocks of 4 min each and ending with a cool down of 3 min normal walking. The perturbations during the four blocks varied in intensity (up to 30 levels of magnitude), four different directions (in mediolateral and anteroposterior axis), perturbed leg side, perturbation time point within the gait cycle, and by conducting dynamic as well as static trials. For session 1, medium intensities and a frequency of around 3 perturbations per minute were chosen based on our experiences from an earlier investigation. The progression in task challenges (i.e., unpredictability of perturbations, belt speed increase, perturbation frequency, dual tasks) was adjusted individually based on a standardized procedure including the judgment of the trainer and the participant using a modified version of the 5 point scale of subjectively perceived difficulty and anxiety during $PBT_{treadmill}$ [18] (online suppl. File 5). This scale was prompted at the end of each training session. Trainers aimed for a mid range in perceived difficulty (i.e., 3/5 = "challenging"), while anxiety should not become too strong (i.e., max. 3/5 = "moderate").

Exercise of Dynamic Stability in the Presence of Perturbations Induced by Unstable Surfaces

This paradigm was designed to train the mechanisms of dynamic stability to improve the ability to regain balance after a perturbation. In addition, the unstable surfaces provoke muscle activation, which is supposed to increase leg strength.

The training was conducted as described by Bohm et al. [16]. Briefly, participants conducted three main exercises (standing, jumping, and lunges) on five different unstable devices (balance cushions, BOSU® balls, balance pads, coordination seesaws, Posturomed®) with plenty of additional challenging tasks (Fig. 2b).

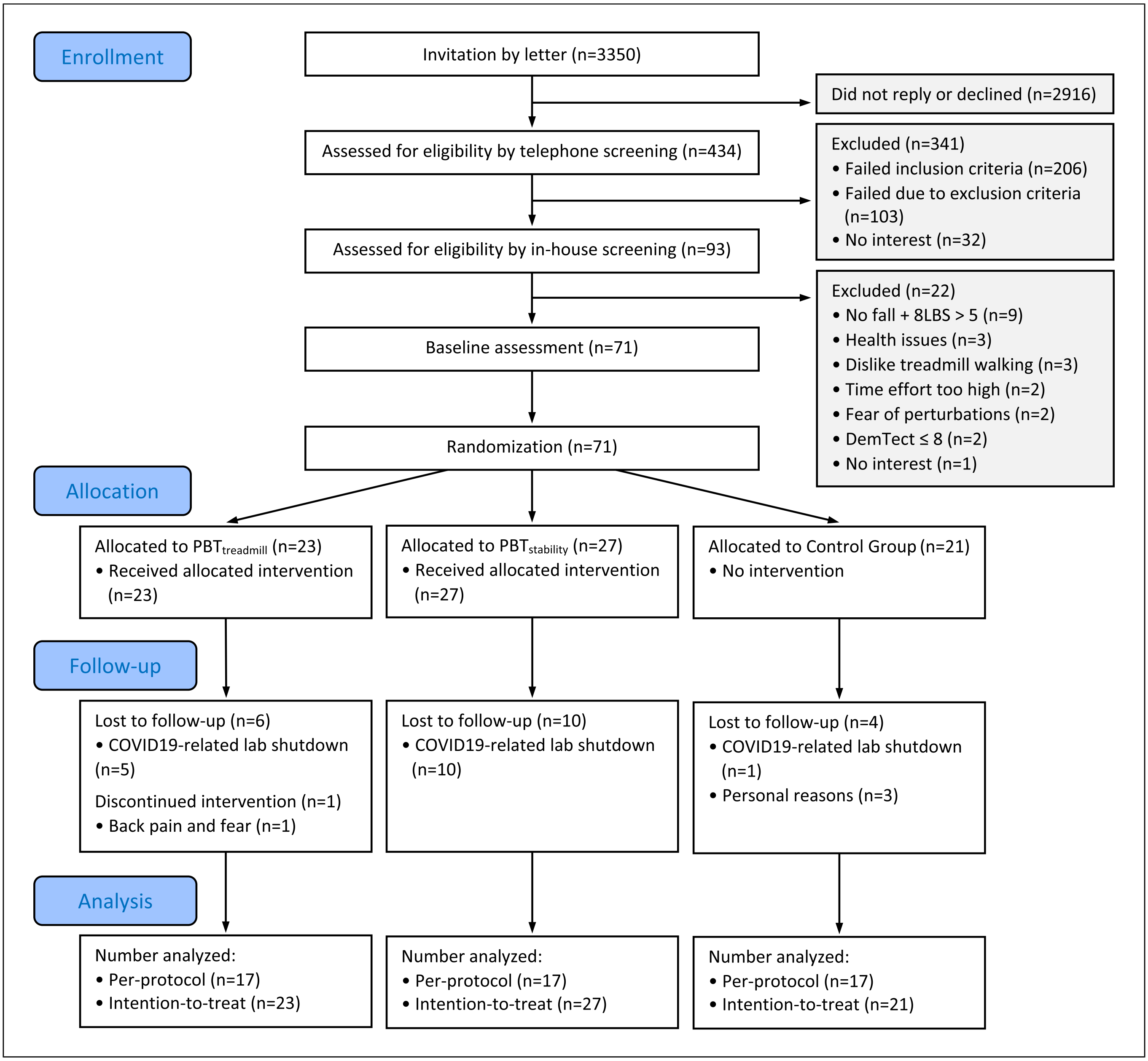

Fig. 1. CONSORT flow diagram. Per protocol analysis considered only participants that finished the experiments. ITT analysis considered all participants that started the trial (by data imputation). $PBT_{treadmill}$: perturbation treadmill training, $PBT_{stability}$: exercise of dynamic stability training in the presence of perturbations.

This training was conducted in small groups of up to ten participants. For our study, a ratio of participants to trainers of 3:1 was chosen.

Each training session started with a 5 min warm up, followed by a circuit training with five stations (i.e., the five unstable devices) and a 3 min cool down. Participants trained in pairs of two. On each station, the following exercises were performed alternating between the two participants: 1 min of standing, 1 min of lunges, and 1 min of jumping. While one participant conducted the task, the other one provided security (and vice versa) by offering grasp support. Participants were asked to train at the border of their stability. This was enabled by a large set of optional challenges (e.g., modification of step width, external manual pushes, closing eyes, crossing arms in front of the chest, catching balls, transition from one device to another, etc.). Lunges were repeatedly held for multiple seconds to promote improvements in leg strength. Trainers supervised the individual training intensities and progression.

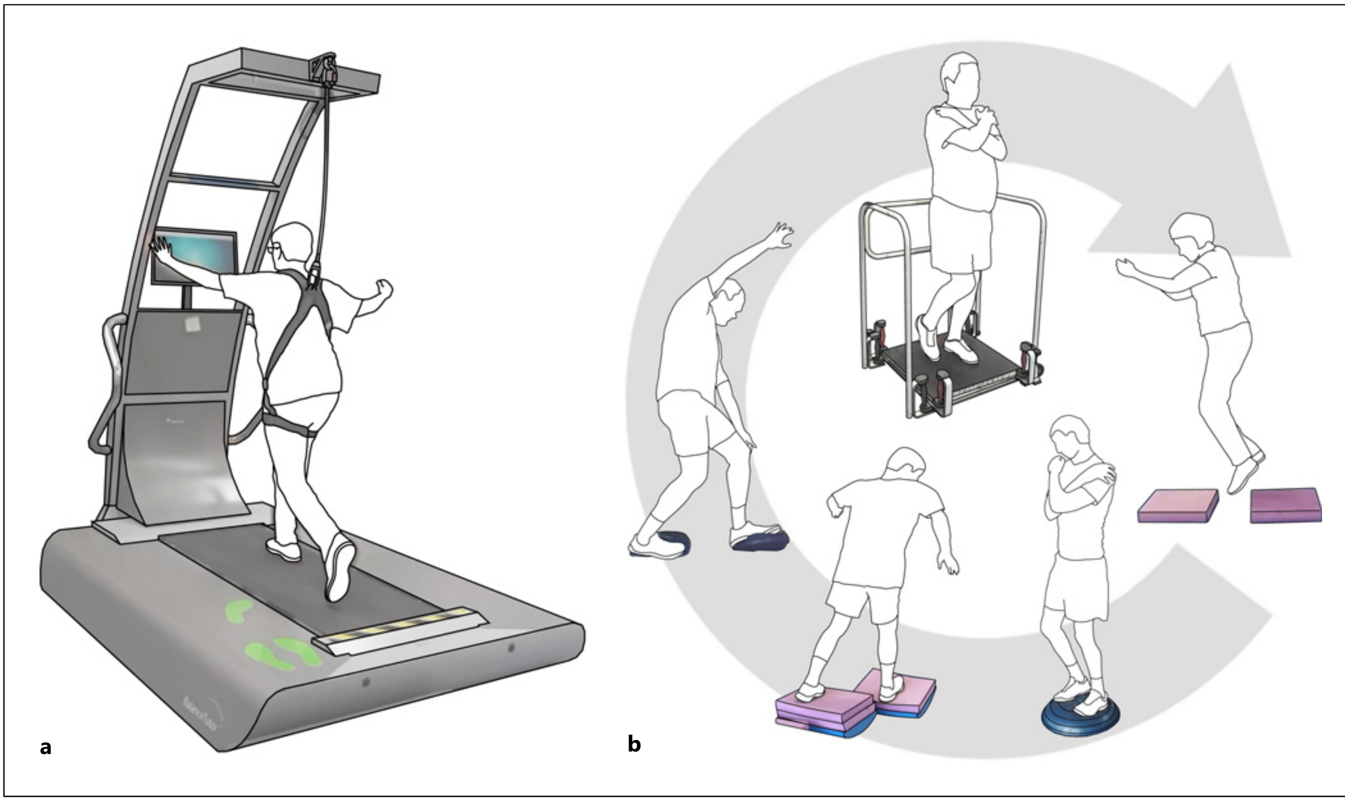

Fig. 2. Schematic figure of the two training paradigms. **a** $PBT_{treadmill}$ with participant training on the perturbation treadmill system. Perturbations were induced by mediolateral platform shifts and acceleration or deceleration of the belt. The screen in front of the participant was only utilized during the trials with announced perturbations, showing a countdown and the direction of the upcoming perturbation. **b** $PBT_{stability}$ with participants training on the five different stations (balance pads, balance half balls, coor dination seesaws, balance cushions, Posturomed). Exercises con sisted of standing, jumping, and lunges on the devices. Plenty of additional challenges were added (e g., external pushes, catching a ball, restricted arm movements, reduced base of support).

Measurements

As the primary outcome, fall risk was determined by the Brief BEST [25] measuring six contexts of balance control: biomechanical constraints (item: hip abduction), stability limits (Functional Reach Forward), anticipatory postural adjustment (Single Leg Stance), reactive postural response (Compensatory Side Stepping), sensory orientation (closed eyes stand on foam), and stability in gait (Timed Up and Go Test). Secondary outcomes included the reactive balance ability, assessed by the Stepping Threshold Test (STT) as described in the study by Adams et al. [26]. For the STT, participants were instructed to use as few steps as possible to react to surface per turbations on a movable platform. The test consisted of six levels with increasing magnitudes where each level included unannounced perturbations in four different directions (anteroposterior and mediolateral) in random order. Single step and multiple thresholds were defined as the lowest level per perturbation direction where the base of support was increased using one single step or multiple steps, respectively. The main score was calculated as the sum of the eight original thresholds [26].

Static balance was assessed by the use of center of pressure (CoP) measures. Participants stood as stable as possible on a force plate (mod. Nintendo Wii Balance Board, A/D converter, 1,000 Hz, 24 bit resolution; Tantor GmbH, Berlin, Germany), with feet hip width apart, hands placed on the hips, and gaze fixed on the wall. A trial was recorded for 40 s, while the first and last 5 s were removed for the analysis of CoP path length to exclude potential fluctuations. The anterior LoS were also acquired on the force plate as conducted by Moreno et al. [27]. Participants stood on the plate with their feet hip width apart, holding the arms beside the torso. Next, they leaned forward as far as they were able to with a fully extended hip without stepping or raising heels. The minimal distance between the anterior border (boundary of the toes) and the CoP position was determined to represent the LoS. For CoP path length and LoS, two trials were performed, while the best ones (i.e., lowest values) were used for analysis. Functional performance was measured by the Timed Up and Go Test [28] (with a fast gait speed [TUG_{fast}]) and the 30 s Chair Stand test [29].

Preferred gait speed was assessed on the GAITRite® system (4.88 m, CIR Systems Inc., Franklin, NJ, USA) [30]. Three subsequent trials with a maximal speed deviation of 10% were averaged.

Isometric leg strength capacity was measured by a standardized test [31]. Participants were sitting with feet attached to the force plate, which was clamped on a custom built bracket (online suppl. File 6). The bracket was attached to the hip (kite harness, Prolimit Kite Waist Pro) with a chain that was individually adjusted aiming for a knee angle of 120°. After a submaximal test trial, participants performed two ramp contractions, where they were instructed to slowly increase the pressure on the force plate before holding the maximum for 3 s. The trials were separated by a 3 min break and the maximum was used for analysis.

The short version of the Falls Efficacy Scale International (Short FES I, German translation) was used for measuring perceived fear of falling [32]. Feasibility was determined by adherence (amount of attended training sessions), adverse events, and the number of dropouts during the interventions.

Statistical Analysis

Group differences in baseline variables were assessed by a one way analysis of variance for metric variables and a χ^2 test for categorical variables. An intention to treat (ITT) approach was used, considering all participants that started the trial. For ITT, a multiple imputation per linear regression was applied, with group and the respective pre value as predictors. Parameter estimates of the conducted 10 im putations were either pooled as provided by SPSS or represented by the median. The missing patterns of the data were monotone, while on average 26% of the values were missing across variables (a detailed overview of missing data is provided in online suppl. File 7).

For an adequate judgment of the robustness of ITT, a per protocol analysis was also conducted, considering only the participants that finished all experiments. For the within group comparison, a two sided dependent *T* test was performed. Between group comparisons were conducted by use of an analysis of covariance with the pre values as a covariate. Effect size as eta^2 and *p* values were reported. An eta^2 from 0.001 to 0.059 indicates small, 0.059 to 0.138 moderate, and above 0.138 large effects [33]. A post hoc test was conducted for every outcome since we were interested in detecting any meaningful dif ference between the two intervention groups as well as between an intervention group and the CG, respectively. Cohen's *d* effect sizes from 0.2 to 0.5 indicate small, 0.5 to 0.8 medium, and above 0.8 large effects [33]. The level of significance α was set to 0.05. Analyses have been conducted in SPSS 26 (IBM Corp., Armonk, NY, USA).

For a sub analysis of the single Brief BEST items, a Wilcoxon signed rank test was performed to determine pre post effects on an item level. Effect size is reported as r [34], where values from 0.1 to 0.3 indicate small, 0.3 to 0.5 medium, and above 0.5 large effects [33]. This analysis has been conducted in R v4.1.2, with the level of significance α set to 0.05.

A sample size calculation was performed in G*Power 3.1 (Heinrich Heine University of Duesseldorf). The following pa rameters were used to determine the required sample size for the analysis of covariance: a large anticipated effect on fall risk ($f = 0.4$), a power of 0.9, number of groups ($n = 3$), and the number of covariates was 1 (i.e., the pre values). Based on that calculation, 83 participants would have been needed. By including a conservative dropout rate of 25%, due to the high demand of PBT [9], an aim of 111 participants was obtained.

Results

Of 3,350 persons contacted by letter, 434 were screened and 71 were finally included (Fig. 1). Twenty-three participants were allocated to $PBT_{treadmill}$, 27 to $PBT_{stability}$, and 21 to the CG. Baseline characteristics did not differ significantly between groups, except for body height (Table 1).

Feasibility Measures

Participants attended 91 ± 9% of training sessions for $PBT_{treadmill}$ and 87 ± 12% for $PBT_{stability}$, with no significant group differences (*p* 0.311). High adherence (>75% of attended training sessions) was achieved by 95% of participants in $PBT_{treadmill}$ and 89% in $PBT_{stability}$.

In $PBT_{treadmill}$, seven participants (30%) had a mild adverse event including muscle or tendon pain. Four participants reported pain in the lower limb region and three participants reported pain in the back region. In $PBT_{stability}$, eight participants (30%) had a mild adverse event. Here, six participants reported pain in the lower limb region and two participants reported pain in the back region. All symptoms disappeared during the intervention period, requiring no medical treatment.

One participant of $PBT_{treadmill}$ dropped out after four training sessions due to reported back pain. This participant also had the highest self-reported levels of anxiety on the training feedback scale (participant's mean of 3.5 vs. $PBT_{treadmill}$ group mean of 1.5 ± 0.7). Sixteen participants (5 $PBT_{treadmill}$, 10 $PBT_{stability}$, and 1 CG) dropped out due to a sudden COVID-19-related shutdown (see online suppl. File 1). Three CG participants did not join the post-assessments (two reported health issues and one was unable to commit time), but two of them were willing to conduct the Short FES-I via telephone.

Training Effects

For the primary outcome (Brief-BEST), the ITT pre-post comparison revealed a statistically significant improvement (*p* 0.002, *d* 0.67) in $PBT_{stability}$, while no significant effects were found in the other groups (Table 2; Fig. 3). The per-protocol approach showed comparable results ($PBT_{stability}$: *p* 0.002, *d* 0.90). The ITT between-group comparison showed a significant group effect (*p* 0.009, η^2 0.131) and the per-protocol approach showed comparable results (*p* 0.055, η^2 0.119). The post hoc analysis of ITT revealed a medium effect in $PBT_{stability}$ compared to $PBT_{treadmill}$ (*p* 0.010, *d* 0.51) and compared to CG (*p* 0.024, *d* 0.52), both in favor of $PBT_{stability}$. These results were also comparable in the per-protocol approach.

The sub-analysis of the single Brief-BEST items (online suppl. File 8) revealed that three out of the six contexts of balance control showed distinct improvements (medium effect sizes $r \geq 0.30$) in $PBT_{stability}$, namely, Single-Leg Stance, Compensatory Side-Stepping, and Functional

Table 1. Characteristics of the study participants at baseline

	$PBT_{treadmill}$ n = 23	$PBT_{stability}$ n = 27	Control n = 21	p value
Age, years	76.5 (5.3)	73.9 (5.9)	74.3 (6.5)	0.281
Female, n (%)	13 (56.5)	15 (55.6)	18 (85.7)	0.057
Weight, kg	70.5 (10.8)	71.7 (11.1)	67.2 (12.0)	0.382
Height, m	1.69 (0.07)	1.71 (0.08)	1.65 (0.07)	0.035
Body mass index, kg/m^2	24.8 (3.8)	24.7 (3.5)	24.6 (3.6)	0.989
Fallers past year, n (%)	10 (44)	15 (56)	8 (38)	0.456
Multiple fallers last year, n (%)	6 (26)	7 (26)	2 (10)	0.300
8-level balance scale (points)	4.1 (1.0)	4.6 (1.2)	4.5 (0.8)	0.295
DemTect (points)	15.7 (2.6)	15.6 (2.5)	15.9 (1.9)	0.926

Values are shown as mean (standard deviation) unless otherwise specified. Group comparison by one-way ANOVA for metric variables and χ^2 test for categorical variables. Fallers past year: participants that reported at least one fall in the past 12 months; multiple fallers last year: participants that reported at least two falls in the past 12 months, 8-level balance scale (static balance test), DemTect (cognitive test). $PBT_{treadmill,}$ perturbation treadmill training; $PBT_{stability}$, exercise of dynamic stability training in the presence of perturbations; ANOVA, analysis of variance.

Reach Forward. In $PBT_{treadmill}$, such improvements were found in Compensatory Side-Stepping.

For secondary outcomes, the ITT pre-post comparison for $PBT_{treadmill}$ showed statistically significant effects in STT ($p < 0.001$, d 1.72), gait $speed_{pref}$ (p 0.002, d 0.70), leg strength (p 0.008, d 0.57), and TUG_{fast} (p 0.048, d 0.43). $PBT_{stability}$ demonstrated significant pre-post effects in gait $speed_{pref}$ (p 0.001, d 0.74), TUG_{fast} (p 0.001, d 0.72), and STT (p 0.007, d 0.58). The CG demonstrated significant pre-post effects in gait $speed_{pref}$ (p 0.014, d 0.54), 30-s Chair-Stand test (p 0.022, d 0.52), TUG_{fast} (p 0.028, d 0.50), and STT (p 0.047, d 0.46). These findings did not alter in the per-protocol approach.

The ITT between-group comparison showed a statistically significant group effect in STT ($p < 0.001$, η^2 0.395) and LoS (p 0.020, η^2 0.110). The post hoc analysis of the STT revealed a strong effect in $PBT_{treadmill}$ compared to CG ($p < 0.001$, d 1.70) and compared to $PBT_{stability}$ ($p < 0.001$, d 1.19), both in favor of $PBT_{treadmill}$. In LoS, a medium effect was found for $PBT_{stability}$ compared to $PBT_{treadmill}$ (p 0.014, d 0.54) and CG (p 0.020, d 0.66), both in favor of $PBT_{stability}$.

$PBT_{treadmill}$ Training Parameters

Participants of $PBT_{treadmill}$ received on average 75.4 ± 13.9 perturbations per training session. The first 21 ± 17% of the perturbation blocks conducted contained announced perturbations. Gait speed increased throughout the intervention by 0.5 ± 0.3 km/h. In the further course, 26 ± 9% of the perturbation blocks included motor and cognitive dual tasks. The mean of perceived difficulty was 2.7 ± 0.4 (3 "challenging") and for perceived anxiety 1.5 ± 0.7 (1 "Not at all," 2 "Just a little") over all sessions in all $PBT_{treadmill}$ participants. Some participants reached maximal perturbation intensities (level 30/30) in a few trials toward the end of the program.

Discussion

Main Findings

We compared two different PBT paradigms systematically with respect to feasibility and fall risk-related outcomes in the domains of balance ability, functional performance, gait speed, leg strength, and perceived fear of falling. Our set of outcome measures revealed similarities and differences between the two training paradigms. Similarities were found in feasibility measures demonstrating high adherence, low intervention-related dropout rate, and no SAEs. Based on these findings, our first hypothesis (i) was supported. With regard to the effectiveness in terms of fall risk reduction, assessed by the Brief-BEST, only $PBT_{stability}$ showed distinct effects compared to CG, but not $PBT_{treadmill}$. Therefore, our second hypothesis (ii) was only partially supported for $PBT_{stability}$. The additional aim of the study was the investigation of training effects on different fall risk-related outcomes. Here, we found task-specific adaptations in the respective intervention groups, demonstrating different training responses associated with the respective PBT paradigm.

Table 2. Results of the within-group and between-group comparison

	Within-group comparison												Between-group comparison						
	$PBT_{treadmill}$				$PBT_{stability}$				contro				ANCOVA		post hoc test				
	Pre	Post	*p*	*d*	Pre	Post	*p*	*d*	pre	post	*p*	*d*	*p*	η^2	Comparison	*p*		*d*	
Brief-BEST	16.7±3.8	17.0±4.3	0.415	0.20	17.1±4.1	18.6±3.8	0.002	0.90	19.1±2.8	19.4±3.1	0.441	0.20	0.055	0.119	TM - STAB	0.029	0.010	0.78	0.51
(points)	16.9±3.5	17.2±4.1	0.457	0.16	17.3±3.8	18.7±3.9	0.002	0.67	18.8±2.7	19.1±3.3	0.552	0.14	0.009	0.131	TM - CG	0.850	0.573	0.07	0.03
															STAB - CG	0.054	0.024	0.69	0.52
STT (points)	24.2±6.1	33.5±5.0	<0.001	1.82	25.5±7.2	28.8±6.1	0.001	0.99	24.8±3.4	27.1±5.5	0.021	0.67	<0.001	0.416	TM - STAB	<0.001	<0.001	1.53	1.19
	24.8±6.0	33.8±5.7	<0.001	1.72	27.0±6.5	29.9±6.8	0.007	0.58	25.6±3.9	27.6±5.8	0.047	0.46	<0.001	0.395	TM - CG	<0.001	<0.001	1.85	1.70
															STAB - CG	0.373	0.137	0.32	0.26
COP_{path}, cm	53.4±33.0	52.0±27.7	0.761	0.07	51.6±22.2	48.2±25.1	0.241	0.30	43.4±23.8	52.7±44.6	0.428	0.20	0.591	0.022	TM - STAB	0.845	0.731	0.07	0.05
	53.5±29.4	53.3±32.5	0.973	0.01	50.3±22.6	48.2±36.7	0.739	0.07	43.2±21.5	52.3±45.7	0.380	0.19	0.516	0.020	TM - CG	0.304	0.275	0.36	0.29
															STAB - CG	0.223	0.208	0.42	0.29
LOS, cm	8.27±1.45	8.44±1.49	0.563	0.14	8.33±1.62	7.87±1.66	0.119	0.40	8.09±1.12	8.37±1.48	0.162	0.36	0.118	0.087	TM - STAB	0.091	0.014	0.59	0.54
	8.15±1.43	8.36±1.70	0.478	0.15	8.03±1.56	7.57±1.78	0.063	0.37	7.93±1.24	8.27±1.68	0.140	0.33	0.020	0.110	TM - CG	0.841	0.609	0.07	0.07
															STAB - CG	0.061	0.020	0.66	0.66
TUG_{fast}, s	8.3±1.4	7.8±1.3	0.027	0.59	7.8±1.4	7.2±1.2	0.002	0.90	7.9±1.1	7.6±1.2	0.009	0.72	0.297	0.050	TM - STAB	0.462	0.412	0.25	0.24
	8.2±1.4	7.7±1.4	0.048	0.43	7.7±1.3	7.0±1.4	0.001	0.72	7.7±1.1	7.4±1.3	0.028	0.50	0.208	0.048	TM - CG	0.522	0.493	0.22	0.11
															STAB - CG	0.172	0.120	0.48	0.40
Chair-	11.6±2.3	12.1±2.6	0.245	0.29	11.6±2.4	12.1.±2.4	0.387	0.22	11.7±1.9	12.8±2.0	0.007	0.75	0.479	0.031	TM - STAB	0.927	0.745	0.03	0.04
Stand (rep.)	11.9±2.2	12.3±2.8	0.374	0.19	12.0±2.4	12.4±2.8	0.506	0.13	12.1±2.1	13.0±2.4	0.022	0.52	0.408	0.027	TM - CG	0.358	0.337	0.32	0.26
															STAB - CG	0.313	0.378	0.35	0.27
Gait speed,	1.21±0.14	1.30±0.17	0.002	0.92	1.18±0.14	1.28±0.15	<0.001	1.18	1.20±0.12	1.28±0.18	0.025	0.60	0.868	0.006	TM - STAB	0.883	0.508	0.05	0.06
m/s	1.23±0.13	1.32±0.18	0.002	0.70	1.21±0.19	1.31±0.22	0.001	0.74	1.21±0.12	1.29±0.14	0.014	0.54	0.548	0.018	TM - CG	0.696	0.626	0.14	0.13
															STAB - CG	0.591	0.323	0.19	0.17
Leg	1,226±450	1,339±352	0.031	0.57	1,250±503	1,308±567	0.104	0.42	1,063±337	1,127±342	0.076	0.46	0.485	0.030	TM - STAB	0.323	0.299	0.34	0.29
strength, *N*	1,205±411	1,325±552	0.008	0.57	1,184±419	1,237±523	0.312	0.20	1,096±334	1,165±360	0.069	0.40	0.255	0.040	TM - CG	0.376	0.232	0.31	0.27
															STAB - CG	0.916	0.504	0.04	0.07
Short FES-	8.8±1.7	8.5±1.7	0.382	0.19	9.0±2.2	8.6±1.5	0.272	0.22	8.7±1.6	8.6±1.8	0.888	0.03	0.884	0.004	TM - STAB	0.858	0.769	0.05	0.08
(points)	8.7±1.7	8.5±1.7	0.467	0.15	9.0±2.2	8.6±1.5	0.262	0.22	8.9±1.8	8.7±1.9	0.660	0.10	0.902	0.003	TM - CG	0.618	0.862	0.15	0.06
															STAB - CG	0.487	0.670	0.21	0.14

Pre- and post-values of the outcomes as mean ± SD. Within-group comparison was done by dependent *t*-test. Between-group comparison was done by ANCOVA. Effect sizes are given as Cohen's *d* and η^2. Results of the per-protocol analyses are presented in black and results of the intention-to-treat analyses in blue. $PBT_{treadmi}$: perturbation treadmill training, $PBT_{stabi\ ity}$: exercise of dynamic stability training in the presence of perturbations; COP_{path}, CoP path length; ANCOVA, analysis of covariance; TM, perturbation treadmill training; STAB, exercise of dynamic stability training in the presence of perturbations; CG, control group.

Feasibility

An adherence of 90% was reached in both programs. This exceeded the suggested threshold of 75% [22, 35] and might have been promoted by the interesting composition of these programs and the benefit expected by the fall-prone individuals. Our results were similar to those of other long-term PBT trials with an adherence of 91% found in healthy older adults in a static surface perturbation training [35] and with 99% in fall-prone older adults in a training of standing and grasping with surface perturbations [12].

To date, very few PBT trials have reported adverse events [20], despite the high task challenge which may result in side effects. Two studies reported adverse event rates of around 25% in PBT with healthy older adults [18, 36]. While no SAEs occurred in our study, mild adverse events were reported in 30% of participants. Such events may be related to intense physical training and might represent physiological adaptations with temporary muscle pain. In general physical exercise therapy, a rate of around 20% of non-serious adverse events is commonly observed [37]. Consequently, it might be speculated that PBT provokes somewhat higher rates of mild adverse events compared to traditional rehabilitation exercise programs, which might be caused by the high intensity of the training.

The dropout rates were very low (PBT$_{treadmill}$: 4%, PBT$_{stability}$: 0%, CG: 14%) after adjusting for the COVID-19 shutdown-related dropouts, which appeared after the intervention phase was successfully finished (online suppl. File 1). The exact reason for the single dropout in PBT$_{treadmill}$ is not clear as the participant reported back pain and anxiety indicated by a high perceived fear during the training. Anxiety-related dropouts have been previously reported in PBT training [20], suggesting that some individuals might need special treatment to reduce fear. The observed dropout rates were lower than the 10–20% frequently reported for balance and exercise programs [23]. This was rather unexpected since the PBT paradigms included challenging tasks of high intensity. Several reasons may account for these low intervention-related dropout rates including the perceived effectiveness, enjoyment, and safety of the programs [38].

Overall, both investigated paradigms showed similarly high adherence, no SAEs, and low dropout rates, demonstrating high feasibility in fall-prone older adults. Importantly, the included population tolerated the high amount of induced perturbations, which was quantified for PBT$_{treadmill}$ as more than 1,150 perturbations during the 6-week intervention. With around 75 perturbations per session, PBT$_{treadmill}$ was quite intense compared with previous PBT studies that included a range of 11–80 perturbations per session [20].

Effects on the Primary Outcome

Fall risk as assessed by Brief-BEST was significantly improved in PBT$_{stability}$ compared to CG but not in PBT$_{treadmill}$. The Brief-BEST sub-analysis revealed that PBT$_{stability}$ induced effects on items associated with different balance domains including static balance (Single-Leg Stance), reactive balance (Compensatory Side-Stepping), and proactive balance (Functional Reach Forward). The PBT$_{stability}$ exercises combined elements of proactive (e.g., self-induced step on an unstable device) as well as reactive balance control (e.g., pushes by the therapist or handling externally induced shifts on the Posturomed). In addition, participants performed perturbation training on an uneven surface in a single-leg stance position, which may explain improvements in this single-leg sub-item of the Brief-BEST. In contrast, PBT$_{treadmill}$ focuses exclusively on reactive balance and effects are reflected by the improvements in the compensatory side-stepping sub-item of the Brief-BEST. These findings are in line with the task specificity of balance training, as described previously [39]. In our study, a transfer of the PBT$_{treadmill}$ effects to other balance domains was limited, presumably related to the high specificity of the underlying neuronal adaptations induced by the training [39].

Effects on Secondary Outcomes

PBT$_{treadmill}$ induced high effects on reactive balance (STT) as compared to CG (d 1.70) and compared to PBT$_{stability}$ (d 1.19). The superiority of PBT$_{treadmill}$ in this outcome is most likely related to the sudden, unannounced nature of the included perturbations, which induced specific improvements in reactive balance control. The perturbation magnitude was larger in PBT$_{treadmill}$ compared to PBT$_{stability}$ which may have led to greater adaptations in recovery performance, as discussed previously [15]. Mansfield et al. [12] also showed substantial improvements in multi-stepping reactions in older adults during a static surface translation after 6 weeks of static perturbation training. In contrast, PBT$_{stability}$ resulted only in small effects compared to CG (d 0.26). Nevertheless, these findings need to be discussed in light of task specificity. The perturbations induced in PBT$_{stability}$ were predictable to a certain degree (e.g., pushes by the therapist, catching a ball, unstable surfaces). These perturbations differed from the unannounced surface-translation perturbations of PBT$_{treadmill}$.

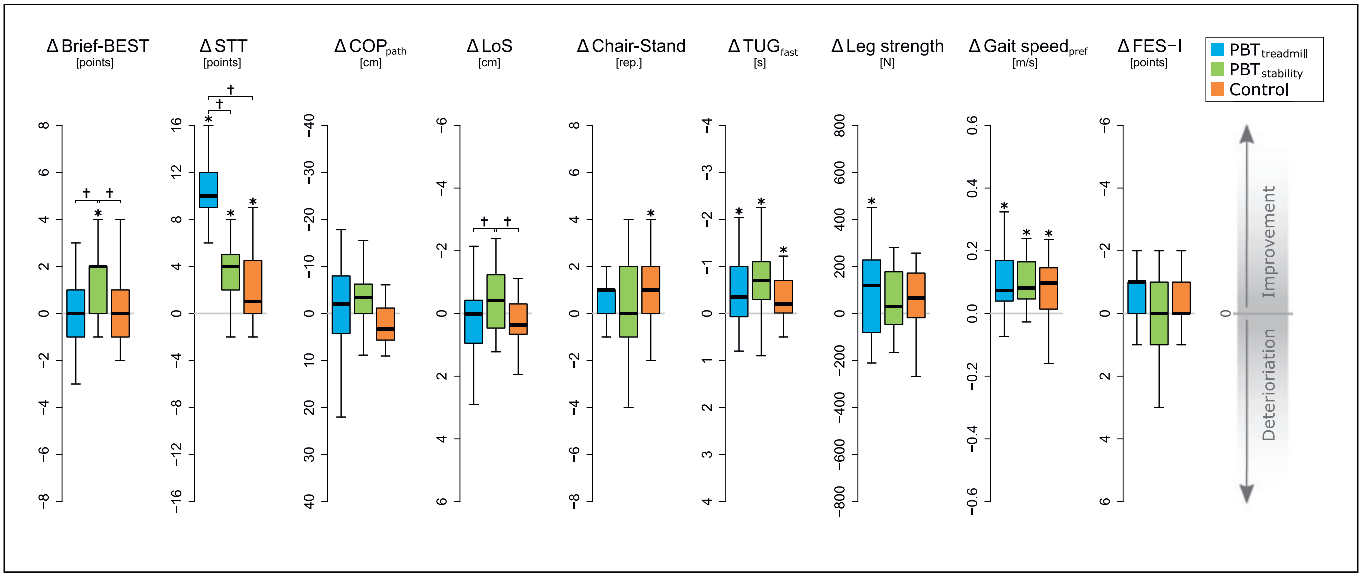

Fig. 3. Pre to post changes (Δ) in the outcomes for each of the three groups. Brief BEST (fall risk scale), STT: Stepping Threshold Test (reactive balance test), COP$_{path}$: path length of center of pressure assessment, LoS: anterior limits of stability, Chair stand: 30 s Chair Stand Test, TUG$_{fast}$: fast version of the Timed Up and Go Test, leg strength: Isometric leg strength capacity, Gait speed$_{pref:}$ preferred gait speed; FES I: short FES I (fear of falling). PBT$_{treadmill:}$ perturbation treadmill training; PBT$_{stability:}$ exercise of dynamic stability training in the presence of perturbations; CG: control group. Significant pre post differences (*) and between group differences (†) are indicated.

The high perturbation task specificity most likely contributed to the higher effects observed in PBT$_{treadmill}$ for the STT. Previous studies on PBT$_{stability}$ have shown positive effects on reactive balance when assessed with the lean-and-release paradigm [14, 16], and these effects might have been masked by the STT in our study.

The limited effects found in static postural stability (COP) might be related to a limited transfer from PBT to other balance domains. Conflicting results for the impact of PBT on COP measures have been published with some studies observing significant improvements [40, 41], while others did not [12, 21]. Therefore, results regarding the effects of PBT on COP measures are inconclusive. Possibly, unspecific effects of PBT appear dependent on baseline levels and the received training dose and intensity that might provoke sufficient adaptations to improve static balance ability.

LoS was only improved in PBT$_{stability}$ (+9%) which is in line with a study investing the same paradigm in healthy older adults over 14 weeks reporting 24% improved LoS in healthy older adults [14]. Greater LoS is achieved by the use of ankle strategy, which was probably improved by the static exercises on the unstable devices in PBT$_{stability}$. In contrast, the static exercises of PBT$_{treadmill}$ included larger and faster surface perturbations that rather provoked usage of the hip strategy [42], which might explain the lack of improvements in LoS for this group.

Taken together, our balance test outcomes provide a clear pattern of task specificity related to the two paradigms. Furthermore, our results demonstrate limited transfer of different reactive paradigms. These findings are in accordance with previous studies that showed that reactive balance tasks were not necessarily improved if they differed from the trained paradigm [13, 43].

In line with previous studies [10, 12, 35, 44], we did not find a group effect in TUG. Similarly, the Chair-Stand test also showed no significant group differences. This test is related to functional strength and endurance, both of which were not primarily addressed by PBT. Consequently, these two fall risk-related clinical tests might not be sensitive to PBT [35] as they do not represent all underlying systems of balance control [45], especially lacking reactive components which are aimed to improve by PBT.

Gait speed also showed no group effect, which is in line with the results of other PBT studies [5, 44]. Still, PBT$_{treadmill}$ contained a large amount of treadmill walking which could have increased the preferred gait speed [46]. However, since baseline values were relatively high in all groups, there was little room for improvement.

Despite an observed lack of group effects, significant pre-post improvements were found for leg strength in $PBT_{treadmill}$ (+9%). This might have been promoted by the fast compensatory steps that were needed to regain balance after the intense static and dynamic perturbations. Leg-extensor strength has been shown to be an important contributor to recovery performance [47]. Consequently, it might be assumed that repetitive exposure to intense perturbations conversely can trigger adaptations in the strength capacity of the legs. In addition, exercising walking might also improve leg strength [48]. However, some other PBT studies did not find effects on muscle strength in healthy older adults [12, 18, 36, 43], but these either included only static perturbation training or only a small amount of training sessions. The descriptive leg strength improvements in $PBT_{stability}$ of 5% lay in between the results of previous studies investigating the same training paradigm in healthy older adults that found improvements of 3–11% in knee extension strength capacity [14, 16].

Limited effects for fear of falling (Short FES-I) were observed possibly related to the low baseline level of the groups which might have inhibited further improvements due to floor effects. Despite the relatively low absolute values of around 9 points (Short FES-I range: 7–28) across all groups and measurement points, this value is still classified as moderate concerns [49]. Other authors also reported limited effects for the FES-I [40, 44] but had small sample sizes which may have limited detecting training effects.

Strength, Limitations, and Future Research

Our study has addressed several research gaps highlighted in recent PBT reviews [20, 50] including (1) a comparison of clinically feasible PBT paradigms [20] that either used a perturbation treadmill with multi-directional perturbations monitored by an individually tailored standardized scale of perceived difficulty and anxiety [20] or a highly applicable low-cost paradigm in a group setting ($PBT_{stability}$), (2) sound measures of clinical feasibility [20], and (3) analyzing PBT effectiveness by presenting effect sizes evaluated under an ITT approach [50]. High external validity is given by our consecutively recruited sample.

High baseline levels in some outcome parameters (i.e., gait $speed_{pref}$ and Short FES-I) may have left limited room for training-induced improvements. However, participants were selected based on fall history and poor balance performance, which does not necessarily result in reduced gait speed or high fear of falling. Additionally, the CG showed unexpected improvements in selected functional and strength tests, which may have masked effects in these secondary outcomes to a certain degree. Another limitation is the sample size of *n* 71. Although this is larger than the majority of PBT intervention studies conducted to date, a higher sample size could potentially verify the difference in the specific measures seen on a descriptive level. Further, it has to be considered that the setting of the paradigms in terms of group versus individual training might have had an influence on the study. However, we partly controlled for this by matching the active training time for both paradigms and by having a low ratio of participants to trainers in the group training, facilitating individualized training feedback. In addition, the equally high levels of training adherence might be an indicator that motivational levels have been comparable in both groups.

Future studies should include reactive tests that differ from the included paradigms for a deeper insight into transfer effects in reactive balance. Finally, larger studies are needed that compare different PBT paradigms with respect to fall rates.

Practical Recommendations

Our study can provide practical recommendations regarding the investigated programs. Based on our results, $PBT_{stability}$ might be recommended for improving balance ability across multiple domains, while $PBT_{treadmill}$ might be recommended for specifically addressing the reactive balance ability. An advantage of $PBT_{treadmill}$ is the high standardization and precise control of the applied perturbations in terms of magnitude. Compared to the perturbation treadmill, the five devices and mats for $PBT_{stability}$ are far less costly. Additionally, $PBT_{treadmill}$ requires a 1:1 trainer-to-participant ratio, while $PBT_{stability}$ is conducted in a group setting. The clinical feasibility was high in both paradigms.

Conclusion

In summary, we found that both investigated paradigms are highly feasible in fall-prone older adults, promoting the integration of PBT into routine care with a low risk for side effects and high rates of adherence. We demonstrated distinct task-specific effects in accordance with balance control theory and the principle of specificity of training. Both paradigms improved fall risk-associated measures which suggests a potential to reduce real-life fall rates.

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Statement of Ethics

All participants gave written informed consent in accordance with the Declaration of Helsinki. The study was approved by the Ethics Committee of Heidelberg University (AZ Schwe 2019/ 1 2).

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

Conceptualization, methodology, and resources: L.B., A.A., and M.S.; validation, visualization, and data curation: L.B ; formal analysis and investigation: L.B. and N.H.; writing original draft: L.B. and M.S.; writing review and editing: L.B., N.H., A.A., and M.S.; supervision: M.S.; and project administration: L.B. and M.S. All authors contributed to the article and approved the submitted version.

Data Availability Statement

All data generated or analyzed for this study are included in this article. Further inquiries can be directed to the corresponding author.

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