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Review Article

Perturbation-Based Balance Training Reduces Falls and Fall Injuries in Older People: Insights on Mechanisms and Training Parameters From a Systematic Review

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A B S T R A C T

Objectives: To evaluate the efficacy of perturbation-based balance training (PBT) in reducing falls, injurious falls, and fall risk factors in older adults.
Design: Systematic review and meta-analysis.
Setting and Participants: Community-dwelling older adults (aged 65 years and older).
Methods: PubMed, CINAHL, EMBASE, and Cochrane databases were searched from inception to June 2024. Randomized controlled trials assessing the effects of PBT on falls or fall risk factors, including reactive balance via laboratory-induced perturbations, were included. Two reviewers independently screened studies and extracted data. Meta-analyses were conducted using a random-effects model, and certainty of evidence was assessed using the Grading of Recommendations Assessment, Development, and Evaluation approach.
Results: PBT significantly reduced fall rates by 23% (rate ratio, 0.77; 95% CI, 0.60-0.99; $I^2 = 57\%$, low certainty) and injurious falls by 24% (rate ratio, 0.76; 95% CI, 0.58-0.98; $I^2 = 0\%$) compared with controls. PBT improved reactive balance (eg, lab-induced falls) but had limited effects on other fall risk factors (eg, gait). In the dosage subgroup analysis, only PBT programs for at least 6 hours reduced falls by 33%.
Conclusions and implications: PBT reduces falls and related injuries, likely through enhanced reactive balance rather than physical improvements. While most PBT programs are low doses (~2 hours), higher doses (6+ hours) likely offer greater fall protection. Further high-quality trials using accessible PBT methods are required to inform policy and guideline development and support scalable implementation of PBT in fall-prevention strategies.

Falls in older people are a global health challenge associated with serious injuries, such as hip fractures and head trauma, hospitalizations, nursing home admissions, fear of falling, poor quality of life, and death.[1,2] Age-related functional declines may be manifested as poor static balance,[3] slow gait,[4] decreased mobility,[5] and poor executive function,[6] which have been the target of many conventional exercise interventions.[7] However, most falls in community-dwelling older people stem from unexpected perturbations such as tripping or slipping while walking.[8] When such a mechanical perturbation abruptly shifts the center of mass beyond the base of support, quick

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and large reactive stepping and sufficient limb support are necessary to avoid falling.[9–11] Reactive balance control against varied perturbations is essential for fall prevention in older adults but is not adequately addressed by conventional exercises.[12]

Perturbation-based balance training (PBT), also known as reactive balance training, is a task-specific intervention designed to enhance reactive balance control through repeated exposure to postural perturbations.[13] Since its emergence in the early 2000s, various modalities of PBT have been explored, including specialized treadmills,[14–16] simulated slips and trips,[17,18] and manual perturbation techniques.[19] Our previous review (2017) involving 7 randomized controlled trials (RCTs) demonstrated that reactive (PBT) and volitional step training could reduce by approximately 50% in older adults.[20] A recent review reported a 39% reduction in falls following reactive balance training[21]; however, this analysis included younger and disease-specific populations, potentially limiting its relevance to older adults.

As the evidence base for PBT continues to expand, inconsistencies across trials have emerged, particularly because of the wide range of perturbation methods used.[22–24] In particular, it remains unclear whether PBT reduces fall-related injuries and improves key fall-risk factors, such as reactive and static balance, gait, mobility, and executive function. In addition, the optimal training parameters, including dosage, perturbation type, and the extent to which PBT should be combined with other exercise modalities, have not been clearly established. It also remains unknown whether intervention effects differ among subgroups of older adults with different levels of fall risk.

This review aims to clarify the efficacy of PBT in reducing falls and fall-related injuries among older adults, while also evaluating its impact on key risk factors. It further explores optimal training parameters and examines whether effects differ across older adults at high vs low risk of falling to inform clinical practice and fall-prevention guidelines.

Methods

Protocol and Registration

This review complies with the Preferred Reporting of Items for Systematic Review and Meta-analysis in the sport and exercise medicine, musculoskeletal rehabilitation, and sports science field (PERSIST).[25] The protocol of the review was prospectively at the International Prospective Register of Systematic Reviews (PROSPERO: CRD42022343368).

Eligibility Criteria

Type of studies

RCTs conducted in all settings were included. Only articles published in English or Japanese were included.

Participants

The population of interest was adults aged 60 years or older. To evaluate the effect on the nondisease-specific population as seen in municipal or open-clinic training programs, we excluded studies that specifically recruited people diagnosed with neurologic diseases (eg, Parkinson's disease, dementia, multiple sclerosis) or conditions (eg, stroke).

Intervention

To be included in this review, studies had to include PBT in at least 1 intervention arm. PBT is defined as *balance training that uses repeated, externally applied mechanical perturbations to trigger rapid reactions to regain postural stability in a safe and controlled environment.*[13]

Comparators

All types of comparators (eg, exercise without perturbation or no intervention) were included. However, studies were excluded if all intervention arms received PBT. If multiple comparators were reported, the most passive comparator was included as the comparator.

Outcome measures

Given their clinical relevance to fall prevention and their frequent reporting in PBT literature, we selected 2 complementary primary outcomes: fall rates and injurious falls. Secondary outcomes included the proportion of fallers and laboratory-based falls as indicators of reactive balance. We also examined measures of static balance (keeping the center of pressure within the static base of support),[26] gait speed, mobility (eg, Timed Up-and-Go test), fear of falling, and other biomechanical markers (eg, margin of stability), to explore broader effects of PBT on fall-related risk factors.

Duration of follow-up

No limitation on the duration of follow-up was imposed. Although if the outcome is assessed at multiple time points, the one closest to 12 months was used.

Information Sources and Search Strategy

Systematic searches were performed in 4 electronic databases (PubMed, CINAHL, EMBASE, and Cochrane) from inception to June 2023. An updated search was conducted in July 2024. The search string was built with a research librarian using key terms for population, intervention, and study design (clinical trials, RCTs). No language restriction was imposed during the database search. Reference lists of included studies and relevant systematic reviews were also manually searched, and experts in the field were contacted to identify any missing studies. The search strategy is available in Supplementary Material (Appendix A).

Study Selection

Two reviewers (I.-Z.S., J.E.N./S.S.) independently screened abstracts and titles based on the eligibility criteria. The reviewers (I.-Z.S., J.E.N./S.S.) also assessed the full text of the retrieved studies to determine inclusion (Supplementary Appendix B). Conflicting opinions were solved by discussions between reviewers and, if necessary, by consulting a third reviewer (M.G.J., Y.O.). The study selection process was conducted in RAYYAN[27] and Covidence (for updated searches).

Data Collection Process

Two reviewers (I.-Z.S., S.S.) independently extracted data in Covidence using a template covering study design, participants, interventions, outcomes, and results. Disagreements were resolved through discussion or additional reviewers (M.G.J., Y.O.). The list of extracted data items is available in the Supplementary Material (Appendix C).

Risk of Bias Assessment

Two authors (S.S., M.B.D.) individually assessed risk of bias (ROB) in the included studies using the Cochrane ROB tool 2.[28] All outcomes were separately assessed using ROB 2. Disagreements during the consensus process were resolved through mutual discussion between reviewers (Y.O., M.G.J.), with final decisions made following appropriate justification. When available, trial protocols and registrations were retrieved and reviewed to supplement information provided in the included studies.

Strategy for Data Analysis

The results from studies with sufficiently similar methodologies were combined in a series of meta-analyses using DerSimonian and Laird inverse variance random-effects model in Cochrane Review Manager software (RevMan 5.0). Fall rates were reported as incidence rate ratios with their corresponding 95% CIs. Binary outcomes, including the proportion of fallers, injurious fallers, and laboratory fallers, were presented as risk ratios (RRs) with 95% CIs. For fall-rate outcomes, person-year denominators were derived by multiplying the number of participants in each trial arm by the reported follow-up duration. This standardized exposure estimate represents the recommended Cochrane approach for calculating event rates when only aggregate follow-up periods are provided. Most included studies indicated the number of participants who completed the follow-up duration. When necessary, this was also confirmed by contacting the authors.[15,23,29] For continuous variables, such as margin of stability, hip height, step height, fear of falling, mobility, static balance, and gait speed, results were reported as mean differences (MDs) or standardized MDs with their respective 95% CIs. Statistical heterogeneity was determined by visual inspection of forest plots and I^2 statistics ($\geq$75%; considerable heterogeneity).

Planned subgroup analyses were conducted to examine the differences in fall rates by (1) participant characteristics (higher risk of falling vs lower risk of falling) (eg, based on fall history, balance impairment), (2) PBT type (walkway vs treadmill vs manual/standing perturbation), (3) training dosage ($\leq$6 hours vs $>$6 hours), and (4) intervention type (PBT alone vs combined PBT, such as PBT plus resistance training), and (5) exercise without perturbation vs no intervention compared with PBT as common comparator. We chose these subgroups because prior evidence suggests that effectiveness varies by dosage, perturbation type, and risk profile.

Sensitivity analyses were performed comparing the results of the low-risk bias studies with the high-risk bias studies. Leave-one-out analyses were performed to assess the robustness of our findings on fall rates and to evaluate whether the exclusion of individual studies significantly altered the overall effect size or heterogeneity.

Publication Bias

Publication bias was assessed by visually inspecting funnel plots to identify potential asymmetry, which could indicate selective reporting of results.

Grading of Evidence

The certainty of evidence was evaluated using the Grading of Recommendations Assessment, Development, and Evaluation (GRADEpro) Guideline Development Tool (Table 1).[30] The overall quality of evidence was determined as high (further research is very unlikely to change our confidence in the estimate of effect), moderate (further research is likely to have an important impact on our confidence in

Table 1
Results of GRADE Evaluation

Certainty Assessment							No. of Patients		Effect		Certainty
No of Studies	Study Design	ROB	Inconsistency	Indirectness	Imprecision	Other Considerations	Perturbation-Based Balance Training	Control	Relative (95% CI)	Absolute (95% CI)	
Number of falls (follow-up: range, 3-12 mo; assessed with: calendars)											
11	Randomized trials	Serious*	Serious†	Not serious	Not serious	None	881/619 (1.42)	842/612 (1.38)	Rate ratio, 0.77 (0.60-0.99)	32 per 100 people per year (from 1.4 to 56 fewer falls)	⨁⨁◯◯ Low*,†
Proportion of fallers (%) (follow-up: range, 3-12 mo; assessed with: calendars)											
11	Randomized trials	Serious*	Not serious	Not serious	Not serious	None	233/621 (37.5%)	282/605 (46.6%)	Rate ratio 0.83 (0.74-0.93)	8 fewer per 100 people per year (from 3 to 12 fewer fallers)	⨁⨁⨁◯ Moderate*
Injurious falls (%) (follow-up: range, 1-12 mo; assessed with: medical record)											
4	Randomized trials	Serious‡	Not serious	Not serious	Serious§	None	76/423 (18.0%)	101/418 (24.2%)	Rate ratio 0.76 (0.58-0.98)	6 fewer per 100 people per year (from 5 to 10 fewer fallers)	⨁⨁◯◯ Low‡,§
Laboratory falls (assessed with: video or harness load cell)											
9	Randomized trials	Serious*	Not serious‖	Not serious	Not serious	None	110/398 (27.6%)	140/283 (49.5%)	Rate ratio 0.42 (0.31-0.58)	29 fewer per 100 people (from 21 to 34 fewer falls)	⨁⨁⨁◯ Moderate*,§,‖

*Downgraded because of concerns with randomization, missing outcome data, outcome measurement, and selective reporting.
†Downgraded because of visual inconsistency and statistical heterogeneity.
‡Downgraded because of ROB: 1 study had high risk, 2 had some concerns, and only 1 had low risk.
§Downgraded because of a relatively low number of events.
‖No downgrade because of heterogeneity not being statistically significant.

the estimate of effect and may change the estimate), low (further research is very likely to have an important impact on our confidence in the estimate of effect and is likely to change the estimate), or very low (any estimate of effect is very uncertain).

Results

Study Selection

The initial search identified 1932 articles after removal of duplicates. Of these, 53 articles were retrieved for full-text assessment, and 23 were identified as meeting all criteria and were thus considered eligible for inclusion in our review. An additional updated search was conducted in July 2024 to include any new studies published while the review was underway. The updated search revealed 144 new studies after the removal of duplicates, and after full-text screening, 2 studies met the inclusion criteria. Consequently, 25 studies were deemed eligible for inclusion after the full-text screening (Figure 1).

Study Characteristics

Of the 25 RCTs included in this review, 6 used perturbation walkaways (eg, sliding tiles, pop-up obstacles),[18,23,31–34] 16 used treadmills (eg, belt accelerations/decelerations),[14–16,22,24,35–43] and 4 used manual/standing perturbations (eg, surface translation)[24,29,44,45] as their PBT modality. Of 25 studies, only 1 study had no intervention for the control group.[36] Rest all other studies had non-PBT exercises. Training doses were >6 hours (average, 9.8 hours) in 7 studies[22,23,29,36,38,39,42] and ≤6 hours (average, 1.6 hours) in the remaining included studies. Eight studies[15,16,29,36,37,42,44,46] included older people at increased risk of falls, whereas the other studies included general samples of older people. A detailed methodology of these RCTs is reported in Supplementary Table 1. The intensity of perturbation was reported inconsistently and often inadequately across studies, with treadmill belt accelerations ranging from 0.1 to 20 m/s^2, and moveable platform slip distances varying from 10 cm to 90 cm. Only 1 study[46] reported the use of harness-supported falls during training.

Results of Syntheses

Effect of PBT intervention on fall outcomes

Eleven trials (n = 1231) included data on total falls (rate ratio) and fallers (RR). Meta-analyses of these trials showed significant reductions in the rate of falls (Figure 2; rate ratio, 0.77; 95% CI, 0.60-0.99; $P = .040$; $I^2 = 57\%$) and proportion of fallers (Figure 3; RR, 0.83; 95% CI, 0.74-0.93, $P = .001$; $I^2 = 0$). A significant reduction in injurious falls was also observed across 4 studies, with a pooled RR of 0.76 (Figure 4; RR, 0.76; 95% CI, 0.58-0.98; $P = .030$; $I^2 = 0\%$).

Effect of PBT intervention on fall-related risk factors

Laboratory-assessed falls related to reactive balance demonstrated a significant reduction following PBT intervention across 9 trials (Figure 5; RR, 0.42; 95% CI, 0.31-0.58; $P < .001$; $I^2 = 38\%$). There were also improvements in margin of stability (5 studies, $n = 381$; MD [m] = 0.47; 95% CI, −0.01 to 0.94; $P = .050$; $I^2 = 68\%$) and hip height (4 studies, $n = 206$; standardized MD [m] = 0.43; 95% CI, 0.05-0.940; $P = .05$; $I^2 = 68\%$). Secondary fall-related risk factors, including

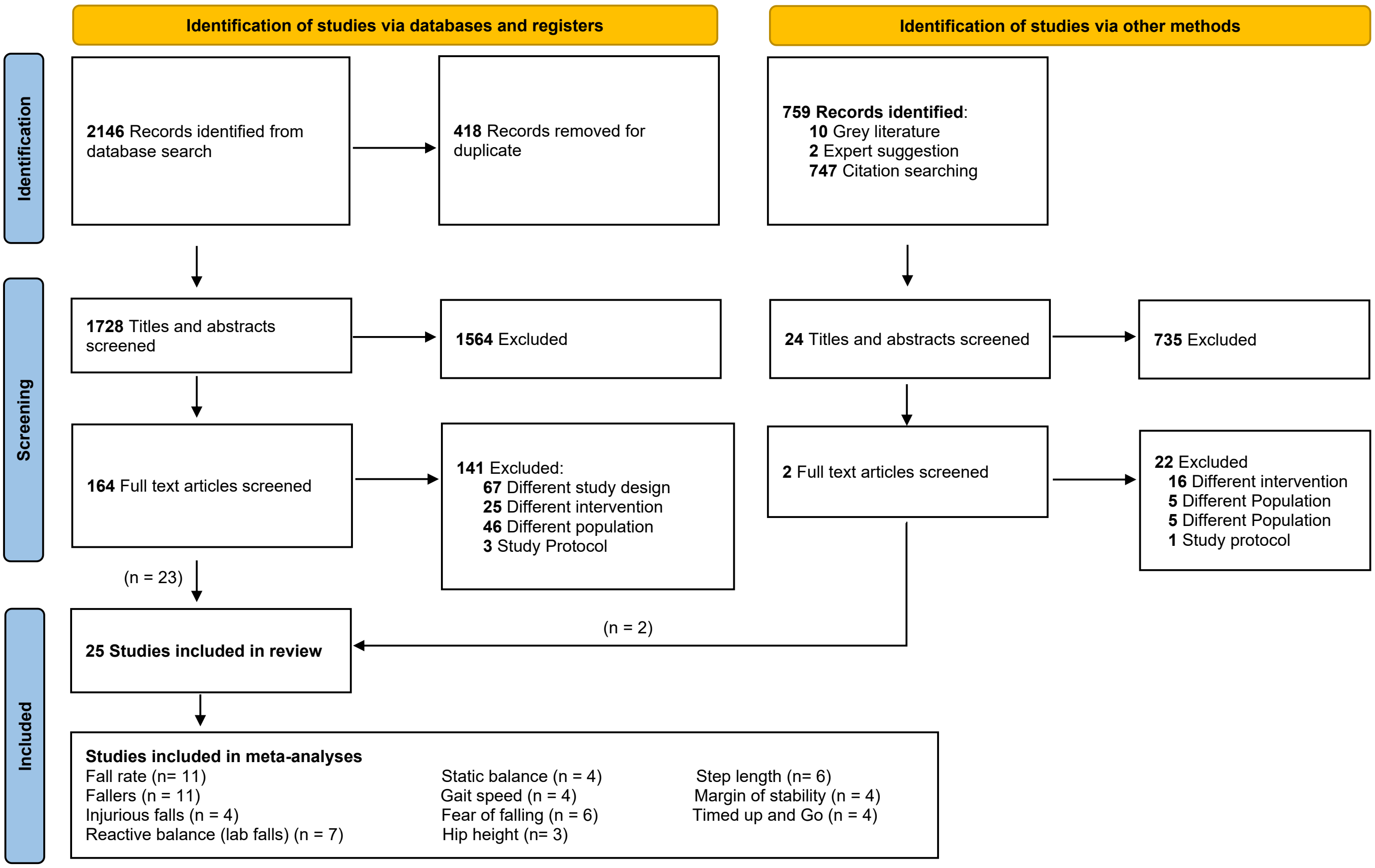


Fig. 1. Flow diagram for this systematic review including searches of databases, registers, and other sources. Studies that reported the outcome of interest were included in the meta-analysis.

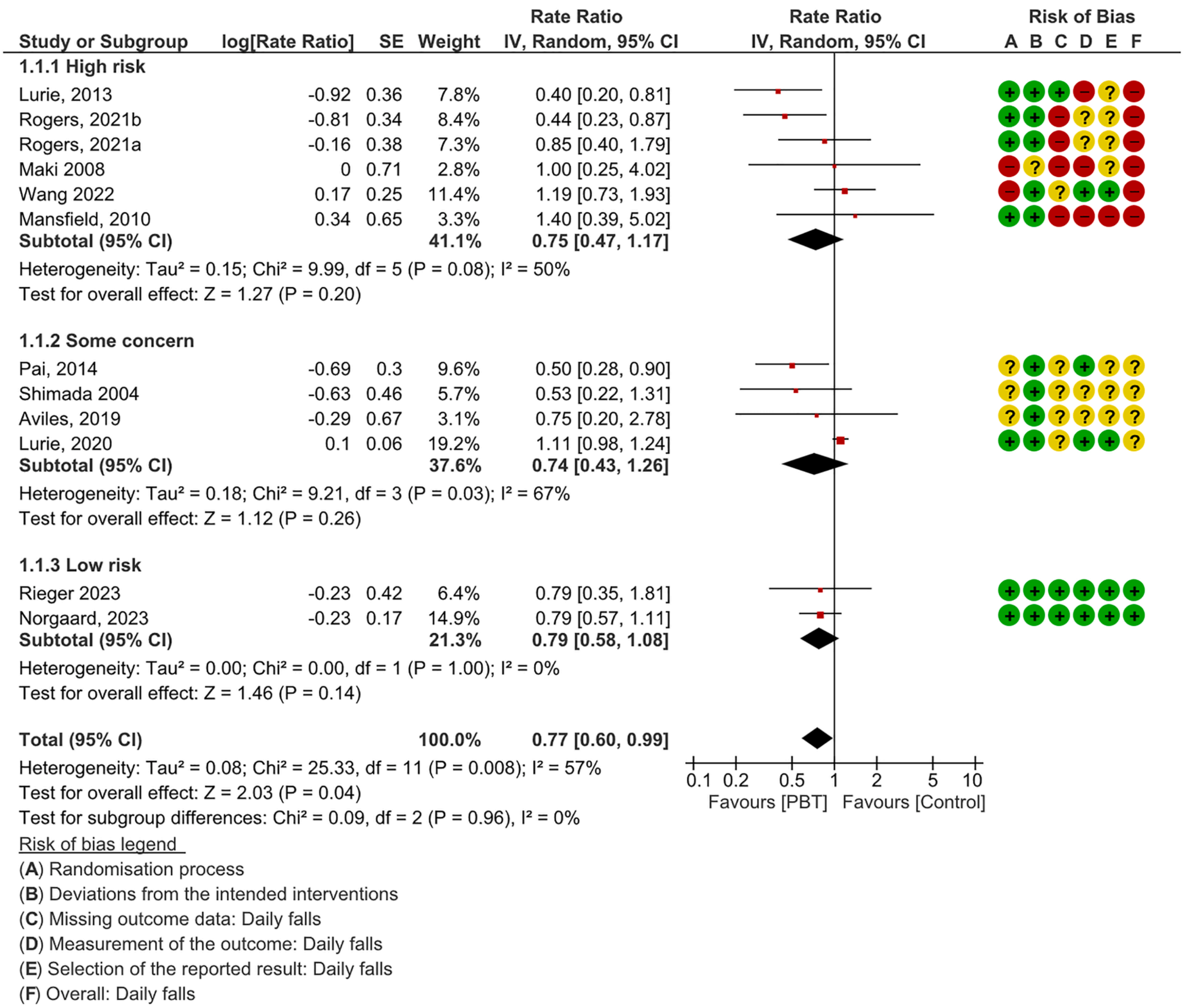


Fig. 2. Result of meta-analyses for rate ratio of falls (Rogers 2021a—induced step training plus hip strengthening vs hip strengthening; Rogers 2021b—induced step training vs flexibility and relaxation).[23] ROB (A) randomization process, (B) deviations from the intended interventions, (C) missing outcome data, (D) measurement of the outcome, (E) selection of the reported result, and (F) overall.

fear of falling (6 studies, $n = 579$), gait speed (5 studies, $n = 126$), static balance (4 studies, $n = 527$), step length (8 studies, $n = 288$), and performance on the Timed Up-and-Go test (5 studies, $n = 418$), were analyzed. However, none of these outcomes demonstrated statistically significant improvements following PBT intervention compared with control groups. Individual forest plots for each factor are presented in the supplementary appendices. Eight studies reported adverse events during training,[15,16,23,32,36,37,39,44] but other 17 studies did not.

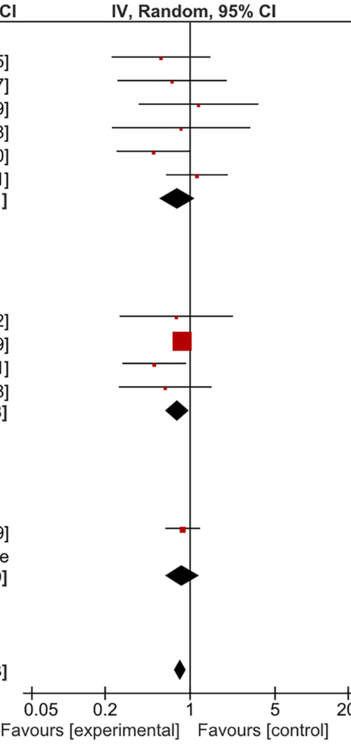
Subgroup Analyses

Since not all included studies reported all secondary outcomes, only studies that reported the outcome of interest were included in the meta-analysis. Forest plots for each subgroup analysis are provided in the online supplementary figures. Regarding combination, PBT combined with exercise significantly reduced falls (rate ratio, 0.26; 95% CI, 0.13-0.54; $P < .001$) but not PBT alone (rate ratio, 0.81; 95% CI, 0.62-1.06; $P = .120$). The falls reduction was significantly greater for PBT combined with exercise (P for subgroup $= .004$). When stratified by training dosage (<6 hours vs 6+ hours), subgroup difference was not significant (P for subgroup $= .46$), but only PBT with higher training dose (>6 hours) significantly reduced falls (rate ratio, 0.67; 95% CI, 0.46-0.97; $P = .03$). Similarly, no significant subgroup differences were observed in participant characteristics (healthy vs high risk, $P = .79$) and PBT type (walkway vs treadmill vs manual/standing; $P = .27$), but only walkway PBT significantly reduced falls (rate ratio, 0.50; 95% CI, 0.28-0.9; $P = .02$). Regarding the control type, no significant subgroup difference was observed between trials comparing PBT against exercise without perturbations and those comparing PBT against no exercise (P for subgroup $= .10$).

Sensitivity Analyses

Sensitivity analysis comparing studies with low vs high ROB revealed no significant difference in effect size for the total number of falls ($P = 1.00$; $I^2 = 0\%$). Influence analysis using a leave-one-out approach for daily falls indicated that the overall effect size became nonsignificant when certain studies,[35,36,45,47] were excluded, with heterogeneity (I^2) ranging from 44% to 59% (Supplementary Appendix D). Notably, heterogeneity was substantially reduced from 55% to 16% when the study by Lurie et al[15] was omitted ($P = .050$).

Study or Subgroup	log[]	SE	Experimental Total	Control Total	Weight	IV, Random, 95% CI	Risk of Bias A	B	C	D	E	F
1.2.1 High risk												
Lurie, 2013	-0.55	0.47	26	33	1.5%	0.58 [0.23, 1.45]	+	+	+	−	?	−
Maki 2008	-0.34	0.52	4	4	1.2%	0.71 [0.26, 1.97]	−	?	−	−	?	−
Mansfield, 2010	0.16	0.57	16	15	1.0%	1.17 [0.38, 3.59]	+	+	−	−	−	−
Rogers, 2021a	-0.17	0.66	24	26	0.8%	0.84 [0.23, 3.08]	+	+	−	?	?	−
Rogers, 2021b	-0.69	0.35	25	26	2.8%	0.50 [0.25, 1.00]	+	+	−	?	?	−
Wang 2022	0.13	0.29	70	63	4.0%	1.14 [0.65, 2.01]	−	+	?	+	+	−
Subtotal (95% CI)			**165**	**167**	**11.3%**	**0.79 [0.57, 1.11]**						
Heterogeneity: Tau² = 0.00; Chi² = 4.25, df = 5 (P = 0.51); I² = 0%												
Test for overall effect: Z = 1.33 (P = 0.18)												
1.2.2 Some concern												
Aviles, 2019	-0.26	0.54	16	15	1.2%	0.77 [0.27, 2.22]	?	+	?	?	?	?
Lurie, 2020	-0.15	0.07	218	212	68.8%	0.86 [0.75, 0.99]	+	+	?	+	+	?
Pai, 2014	-0.68	0.3	102	96	3.7%	0.51 [0.28, 0.91]	?	+	?	+	?	?
Shimada 2004	-0.47	0.44	15	11	1.7%	0.63 [0.26, 1.48]	?	+	?	?	?	?
Subtotal (95% CI)			**351**	**334**	**75.5%**	**0.79 [0.63, 0.98]**						
Heterogeneity: Tau² = 0.01; Chi² = 3.41, df = 3 (P = 0.33); I² = 12%												
Test for overall effect: Z = 2.14 (P = 0.03)												
1.2.3 Low Risk												
Norgaard, 2023	-0.14	0.16	70	70	13.2%	0.87 [0.64, 1.19]	+	+	+	+	+	+
Rieger 2023	-0.21	0.43	35	34		Not estimable	+	+	+	+	+	+
Subtotal (95% CI)			**70**	**70**	**13.2%**	**0.87 [0.64, 1.19]**						
Heterogeneity: Not applicable												
Test for overall effect: Z = 0.88 (P = 0.38)												
Total (95% CI)			**586**	**571**	**100.0%**	**0.83 [0.74, 0.93]**						
Heterogeneity: Tau² = 0.00; Chi² = 7.81, df = 10 (P = 0.65); I² = 0%												
Test for overall effect: Z = 3.18 (P = 0.001)												
Test for subgroup differences: Chi² = 0.27, df = 2 (P = 0.87), I² = 0%												



Risk of bias legend
(**A**) Randomisation process
(**B**) Deviations from the intended interventions
(**C**) Missing outcome data: Daily falls
(**D**) Measurement of the outcome: Daily falls
(**E**) Selection of the reported result: Daily falls
(**F**) Overall: Daily falls

Fig. 3. Result of meta-analyses for RR (fallers) (Rogers 2021a—induced step training plus hip strengthening vs hip strengthening; Rogers 2021b—induced step training vs flexibility and relaxation).[23] ROB (A) randomization process, (B) deviations from the intended interventions, (C) missing outcome data, (D) measurement of the outcome, (E) selection of the reported result, and (F) Overall.

Publication Bias

Due to the limited number of included studies, the funnel plots for the total number of falls, the number of fallers, and the injurious falls lacked a discernible funnel shape, preventing meaningful interpretation (Supplementary File). However, the funnel plot for laboratory falls indicated potential publication bias. Upon removal of suspected outlier studies,[35,36,45,47] the effect size was no longer statistically significant, suggesting that these studies may have disproportionately influenced the original findings.

ROB and Certainty of Evidence

The GRADE assessment indicated that the certainty of evidence was low for outcomes related to risk of falls, injurious falls, and moderate for the risk of fallers and laboratory-assessed falls. These ratings were primarily influenced by methodological limitations across the included studies, such as lack of concealed allocation, the absence of blinding procedures, potential selective outcome reporting, and incomplete outcome data because of attrition.

Discussion

This review revealed that PBT reduced fall rates in community-dwelling older adults by 23% compared with control groups receiving exercise without perturbation or no exercise/intervention. However, the certainty of this evidence was rated as low. Similarly, PBT was associated with a 24% reduction in injurious falls, also supported by low-certainty evidence. In contrast, the proportion of older adults experiencing at least 1 fall decreased by 17%, with moderate certainty in the estimate. PBT enhanced reactive balance responses to sudden perturbations. PBT did not significantly affect static balance, gait speed, or fear of falling, suggesting that fall reduction might stem from improved reactive balance rather than broader physiological or psychological changes.

Mechanisms

PBT differs fundamentally from traditional balance training.[24,48,49] While conventional exercises often focus on maintaining the center of mass within a reduced base of support (eg, single-leg stance), PBT targets reactive balance, that is, the ability to recover from sudden, unexpected perturbations. This is a critical mechanism of fall prevention that conventional programs do not adequately address.[13,50] PBT achieves this by exposing individuals to repeated, controlled perturbations, allowing them to develop predictive and reactive motor strategies to maintain balance.

Improved Reactive Balance and Transfer to Daily Life

The review found that PBT was associated with a 58% reduction in laboratory-induced falls, suggesting an improvement in reactive

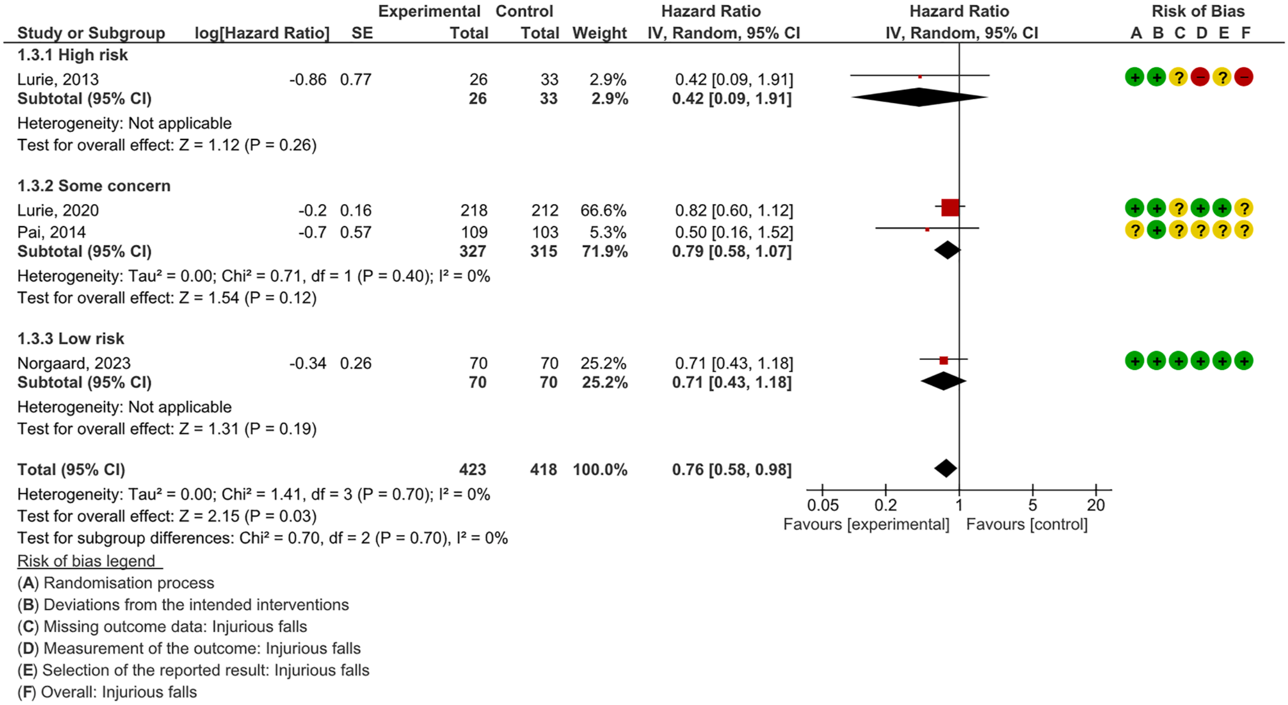


Fig. 4. Result of meta-analyses for RR (Injurious falls). ROB (A) randomization process, (B) deviations from the intended interventions, (C) missing outcome data, (D) measurement of the outcome, (E) selection of the reported result, and (F) overall.

balance. Further, the reduction in real-world falls was more dampened at approximately 25%. This difference may reflect the complexity and unpredictability of real-life environments, which current PBT protocols may not fully replicate.[51,52] Moreover, many PBT programs are delivered over short timeframes, and their protective effects may diminish over time. For instance, 1 trial reported a 57% reduction in injurious falls at 3-month follow-up, but this benefit was lost at 12 months.[15] These findings highlight the potential value of booster sessions to maintain long-term benefits.[53]

Biomechanical outcomes also support the efficacy of PBT. Improvements were observed in the margin of stability and hip height, suggesting enhanced postural control. However, changes in other measures, such as recovery step length, were not significant, likely because of variability in perturbation types (eg, slips vs trips), which elicit different motor adaptations.[52] This underscores the need for more standardized outcome measures in future studies.

Dose and Intensity of PBT

Interestingly, most PBT programs included in this review involved relatively low training doses, averaging just 1.6 hours across 3 to 6 sessions. This suggests that PBT may reduce falls through motor learning, enabling quick gait and posture adaptation. Studies show that older adults often adjust within 3 to 24 trials in a single session using predictive strategies like forward center-of-mass shifts.[17,18,54] However, in the dosage subgroup analysis, only PBT programs with at least 6 hours reduced falls by 33%. While optimal training dose may vary for each individual, several hours of PBT may be necessary to develop familiarity with perturbations, learn effective reactive balance strategies, and automate these responses,[32,55] especially in frailer individuals who benefit from gradual progression starting from lower-intensity perturbations. However, 6 hours is still substantially lower than the recommended dose for conventional exercises (3 hours/wk on an ongoing basis).[49]

Due to the inherent heterogeneity of PBT methods, the intensity of interventions has been reported inconsistently and lacks reproducibility across studies. We recommend that future research consistently report the number and rate of harness-supported falls as a universal and objective indicator of PBT intensity.[46] Incorporating such measures may facilitate tailored interventions and enhance clinical outcomes.

Different PBT Methods

Subgroup analyses did not reveal statistically significant differences between PBT delivery methods—such as treadmills, walkways, or manual/standing perturbations. However, walkway interventions showed a larger effect size, suggesting a potential trend toward greater efficacy. Some studies report generalization of skills from treadmill to overground settings, whereas others highlight distinct adaptations and limited transferability.[51,52,56] These mixed findings question whether all PBT modalities are equally effective, underscoring the need to identify methods that best mimic real-world perturbations.

Complementing Conventional Exercise

Since PBT did not significantly improve other risk factors, balance, gait speed, or fear of falling, in our opinion, it should be considered a complementary intervention rather than a substitute for conventional exercise. Notably, subgroup analysis based on 1 study revealed that combining PBT with lower-limb strength training reduced falls by 74%, a significantly greater effect than PBT alone. This supports the idea that muscle strength, particularly in the hips, is essential for executing rapid reactive steps.[23,57] As it is a single-study analysis, the conclusion remains uncertain, and future research should focus on this approach. For now, we suggest integrating PBT with traditional strength and balance exercises, as this combination may offer synergistic benefits and address multiple fall risk factors. In addition, there was no significant subgroup difference when comparing exercise without

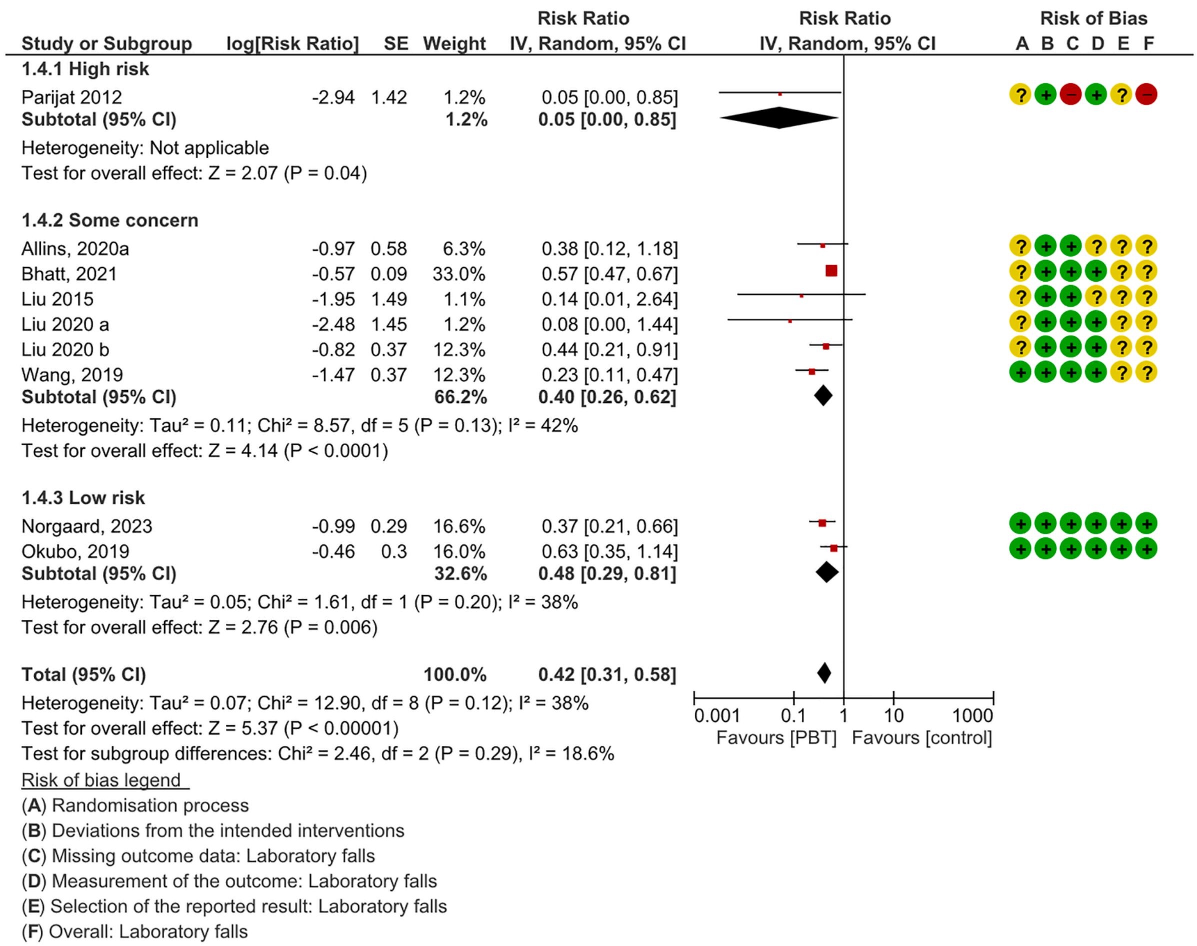


Fig. 5. Result of meta-analyses for RR (laboratory fallers) (Liu 2020a—overground slip-perturbation training vs Ot: overground slip-perturbation training; Liu 2020b—treadmill perturbation training vs treadmill control;[34] Allins 2020a—slip training vs control). ROB (A) randomization process, (B) deviations from the intended interventions, (C) missing outcome data, (D) measurement of the outcome, (E) selection of the reported result, and (F) overall.

perturbation and no exercise against PBT. However, it is noteworthy that PBT reduced falls by 45% compared with no exercise ($P = .02$) but only by 13% compared with exercise without PBT ($P = .24$).

Clinical Implications

PBT effectively improves reactive balance and should be integrated into fall prevention programs for both healthy and high-risk older adults. Brief PBT sessions can provide benefit, but programs should aim for higher doses (≥6 hours) when feasible to achieve sustainable neuromuscular adaptations. Combining PBT with exercise might offer synergistic benefits. Manual perturbations are practical and of low cost for widespread implementation, whereas walking-based perturbations may enhance generalizability to real-life situations when resources allow. However, given the low certainty of the current evidence, more rigorous high-quality trials are needed.

Strengths and Limitations

A major strength of this review is the substantial number of included studies, which enabled previously unexplored subgroup analyses and provided clinically relevant insights into the effectiveness and practical application of PBT. The fall-related outcomes are comprehensive, covering fall rate, proportion of fallers, injurious falls, and key risk factors including reactive balance. Finally, the use of the GRADE framework clearly communicates the confidence in each finding to support informed clinical and research decisions.

Despite its strengths, this review has several limitations. First, the possibility of publication bias and missed studies in including those not published in English or Japanese cannot be ruled out. Second, there was substantial heterogeneity in PBT protocols, including differences in training modality, dosage, and delivery, which may have influenced the pooled results. Third, although sensitivity and subgroup analyses were conducted, these 1-dimensional approaches cannot fully account for the complex confounding present across studies. Fourth, moderate heterogeneity ($I^2 = 55\%$) was observed in the meta-analysis, which was reduced to 16% upon excluding Lurie et al,[15] indicating it may have disproportionately contributed to between-study variability, likely because of its pragmatic design and lack of a standardized PBT protocol (eg, session range, 1-25). Fifth, this review focused on studies involving community-dwelling older adults, so the generalizability of these findings to those living in supported care or with neurologic conditions remains uncertain. Last, the limited number of studies included, and their methodological weaknesses, resulted in low to moderate certainty of evidence. These limitations highlight the need for high-quality, standardized trials to strengthen the evidence base and clarify optimal PBT practices.

Conclusions and Implications

This review provides evidence that PBT reduces all fall rates in older adults compared with exercises without perturbation or no exercise. PBT clearly improves reactive balance control, as indicated by a 58% reduction in laboratory-induced falls and improved dynamic stability following perturbations. Low-dose PBT (1.5 hours) likely promotes rapid motor learning and anticipatory strategies, whereas high-dose PBT (>6 hours) may drive more sustainable, generalizable neuromuscular adaptations for fall prevention. Combining PBT with exercise may offer synergistic benefits, as PBT alone may not improve other risk factors. Evidence for delivery methods is mixed: fall reduction was demonstrated clearly in walkway-based PBT, whereas differences from treadmill-based and manual PBT remain inconclusive. Thus, manual/standing perturbation techniques remain a feasible, low-cost option for clinical implementation.

Overall, PBT is a clinically relevant and effective intervention that can be integrated into routine exercise programs to strengthen fall prevention strategies in older adults. Given the limited evidence, high-quality trials using accessible and scalable PBT delivery methods are needed to confirm its effectiveness for widespread community implementation.

Patient Involvement and Consent

This review did not involve human participants; therefore, patient involvement and consent were not required.

Ethics Approval

Although this review did not involve human participants, the authors adhered to principles of equity, diversity, and inclusion in the conduct and reporting of this work.

Data Sharing Statement

All data relevant to this study are included within the article and supplementary material. For additional queries, readers are requested to contact the corresponding author.

PROSPERO Registration: CRD42022343368.

Disclosure

The authors declare no conflicts of interest.

Supplementary Data

Supplementary data related to this article can be found online at https://doi.org/10.1016/j.jamda.2026.106316.

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