

BMJ Open Perturbation-based balance training of older adults and effects on physiological, cognitive and sociopsychological factors: a secondary analysis from a randomised controlled trial with 12-month follow-up

Jens Eg Nørgaard ^{1,2}, Stig Andersen ^{1,2}, Jesper Ryg ^{3,4},
Jane Andreasen,^{5,6,7} Anderson de Souza Castelo Oliveira,⁸
Andrew James Thomas Stevenson ⁶, Mathias Brix Brix Danielsen ^{1,2},
Martin Gronbech Jorgensen ^{1,2}

To cite: Nørgaard JE, Andersen S, Ryg J, *et al.* Perturbation-based balance training of older adults and effects on physiological, cognitive and sociopsychological factors: a secondary analysis from a randomised controlled trial with 12-month follow-up. *BMJ Open* 2024;**14**:e080550. doi:10.1136/bmjopen-2023-080550

► Prepublication history and additional supplemental material for this paper are available online. To view these files, please visit the journal online (<https://doi.org/10.1136/bmjopen-2023-080550>).

Received 04 October 2023
Accepted 09 July 2024



© Author(s) (or their employer(s)) 2024. Re-use permitted under CC BY-NC. No commercial re-use. See rights and permissions. Published by BMJ.

For numbered affiliations see end of article.

Correspondence to

Dr Martin Gronbech Jorgensen; mgi@rn.dk

ABSTRACT

Background Perturbation-based balance training (PBT) has shown promising, although diverging, fall-preventive effects; however, the effects on important physical, cognitive and sociopsychological factors are currently unknown. The study aimed to evaluate these effects on PBT at three different time points (post-training, 6-months and 12-months) in community-dwelling older adults compared with regular treadmill walking.

Methods This was a preplanned secondary analysis from a randomised, controlled trial performed in Aalborg, Denmark, between March 2021 and November 2022. Community-dwelling older adults aged ≥65 were randomly assigned to participate in four sessions (lasting 20 min each) of either PBT (intervention) or regular treadmill walking (control). All participants were assigned to four testing sessions: pretraining, post-training, 6-month follow-up and 12-month follow-up. At these sessions, physical, cognitive and sociopsychological measures were assessed.

Results In total, 140 participants were randomly allocated to either the PBT or control group. Short-term (pretraining to post-training) between-group differences were seen for choice stepping reaction time (−49 ms, 95% CI −80 to −18), dual-task gait speed (0.05 m/s, 95% CI 0.01 to 0.09) favouring the PBT group. However, these improvements were not sustained at the 6-month and 12-month follow-up. No significant between-group differences were found in other physical, cognitive or sociopsychological factors.

Conclusions This study showed that PBT, in the short term, improved choice stepping reaction time and dual-task gait speed among community-dwelling older adults. Yet, these improvements were not retained for 6- or 12-months. The healthy state of the study's population may have imposed a ceiling effect limiting the ability to show any clinically relevant effects of PBT.

Trial registration number [NCT04733222](https://www.clinicaltrials.gov/ct2/show/study?term=NCT04733222).

STRENGTHS AND LIMITATIONS OF THIS STUDY

- ⇒ This randomised controlled trial was preregistered in ClinicalTrials.gov, a protocol was published, and it followed CONSORT statement.
- ⇒ Due to practical limitations and the nature of training interventions, the outcome assessor of these secondary outcomes and participants were not blinded for group allocation.
- ⇒ The study population was a convenience sample of low-risk older adults with no specific physical, cognitive or sociopsychological problems.

INTRODUCTION

Ageing leads to deteriorations in physical and cognitive functions, increasing the risk of falls and fall-related injuries, such as fractures.^{1–3} However, falls not only lead to physical but also psychological consequences, as falling has been associated with developing concerns about falling.⁴ These physical and cognitive consequences of falls collectively lead to disability and loss of independence, which greatly impact the quality of life of older adults.⁵ Additionally, society is substantially burdened by fall-related costs, accounting for approximately 1% (0.8% to 1.5%) of healthcare expenses in developed countries.⁶ Thus, effective and sustainable fall-preventive interventions are needed to improve the well-being of older adults and limit societal costs.⁷

Currently, physical exercise is considered the most effective fall-preventive intervention.⁸ A systematic review of 64 randomised, controlled trials on general physical exercise identified a 23% reduction in fall rates.⁹ Most of the studies in this review employed conventional training approaches targeting specific

physical functions associated with fall risk such as muscle strength or balance.⁹ Thus, besides preventing falls, they also help maintain activities of daily life function which is important for preserving the independence and quality of life of older adults.^{10 11} However, indirectly targeting falls by improving risk factors may not be the most effective approach.⁹ Indeed, the well-established principle of task-specificity states that training paradigms are most effective when they closely simulate the desired task.^{12–14} Among community-dwelling older adults, most falls are caused by slips and trips during walking.^{2 15 16} Hence, interventions emphasising rapid compensatory reactions following slips and trips may prove more effective in fall-prevention compared with conventional approaches.^{15 17}

One such intervention is perturbation-based balance training (PBT), in which the participants are exposed to repeated, unexpected postural disturbances while wearing a body harness to ensure their safety.¹⁸ It is well documented that PBT leads to considerable reactive balance adaptations after even short exposures, which can be retained for up to a year in laboratory settings.^{18–21} Yet, divergent effects of PBT on daily life falls have been reported, with some showing an approximate 50% decrease while others find no effects, including the primary analysis from the current study, which showed a non-significant decrease in fall rates of 22% (Incidence Rate Ratio 0.78, 95% CI 0.44 to 1.39).^{18 22–24} Moreover, additional benefits of PBT on other physical, cognitive and sociopsychological factors are vastly unknown. Considering that the laboratory reactive balance adaptations are long-lasting, evaluating the long-term (> 6 months) maintenance of additional adaptations is of special interest. The long-term effects of PBT have previously been explored in patients with Parkinson's disease and spinal cord injury^{25–28} and short-term effects in community-dwelling older adults.²⁹ Therefore, this preplanned secondary analysis of a randomised, controlled trial with a 12-month follow-up aimed to evaluate the short-term and long-term effects of a four-session PBT intervention on physical (gait, static balance, choice stepping reaction time, lower extremity performance), cognitive (executive function) and sociopsychological (concerns about falling and quality of life) measures among community-dwelling older adults aged 65 years or older, compared with regular treadmill walking.

METHODS

Trial design

This article reports secondary results from a parallel group (1:1 ratio), randomised, controlled trial with a 12-month follow-up. A trial protocol and statistical analysis plan have been preregistered at ClinicalTrials.gov (NCT04733222), and a protocol has been published.³⁰ The primary outcome was fall rates and these results have already been reported.³¹ There were no deviations from the protocol. The reporting of this article adheres to the Consolidated Standards of Reporting Trials (CONSORT) 2010 guidelines.³²

Participants

Eligible participants had to be (1) 65 years or older, (2) community-dwelling and (3) able to walk without a walking aid. Individuals were excluded if they (1) had an unstable medical condition that prevents safe participation, (2) had a severe cognitive impairment (defined as a score of 8 or less on the Short Orientation-Memory-Concentration test), (3) were currently participating in another fall-preventive trial or (4) had any of the following self-reported conditions: orthopaedic surgery within the past 12-months, osteoporosis or history of osteoporosis-related fractures (low impact hip, spine and wrist fracture) or progressive neurological disease (eg, Parkinson, multiple sclerosis).

The participants were recruited through advertisements on local radio and national television spots. Testing and training sessions were conducted at a laboratory at Aalborg University (Department of Health, Science and Technology, Fredrik Bajers Vej 7A2-107, DK-9000, Aalborg, Denmark).

Interventions

All participants were assigned to four training sessions (see figure 1). The initial two sessions were conducted on the first day at the laboratory. A week later, the third training session was performed while the fourth served as a booster session 6 months after the third session.

The training interventions were performed on the same Woodway split-belt treadmill, moving uniformly (Split 70/157/ASK; Woodway, Weil am Rhein, Germany). Before training commencement, the preferred treadmill walking speed was determined by increasing and decreasing the belt speed until the upper and lower boundary of comfortable walking was identified. The preferred walking speed was then defined as the average of this upper and lower boundary.

Perturbation-based balance training (intervention)

A detailed description of the PBT protocol has been published elsewhere.³⁰ In brief, participants allocated to the PBT group were exposed to 40 perturbations applied bilaterally at each session. The first session consisted only of slips, the second only trips while the third and the fourth had randomly mixed slips and trips. The timing (10–50 steps) and side (left or right) of the perturbations were randomised to enhance their unpredictability. The slips (backward loss of balance) were induced by a sudden forward acceleration resulting in a reversal in the belt movement direction at the heel strike. The trips (forward loss of balance) were provoked by an initial small deceleration followed by a larger backward acceleration at the mid-swing phase of the gait cycle. The perturbations were triggered by a heel contact placed under the sole of the left foot using the computer software Mr. Kick III (Knud Larsen, Department of Health, Science and Technology, Aalborg University, Denmark).

The perturbation intensity depended on the preferred walking speed and was divided into five levels with

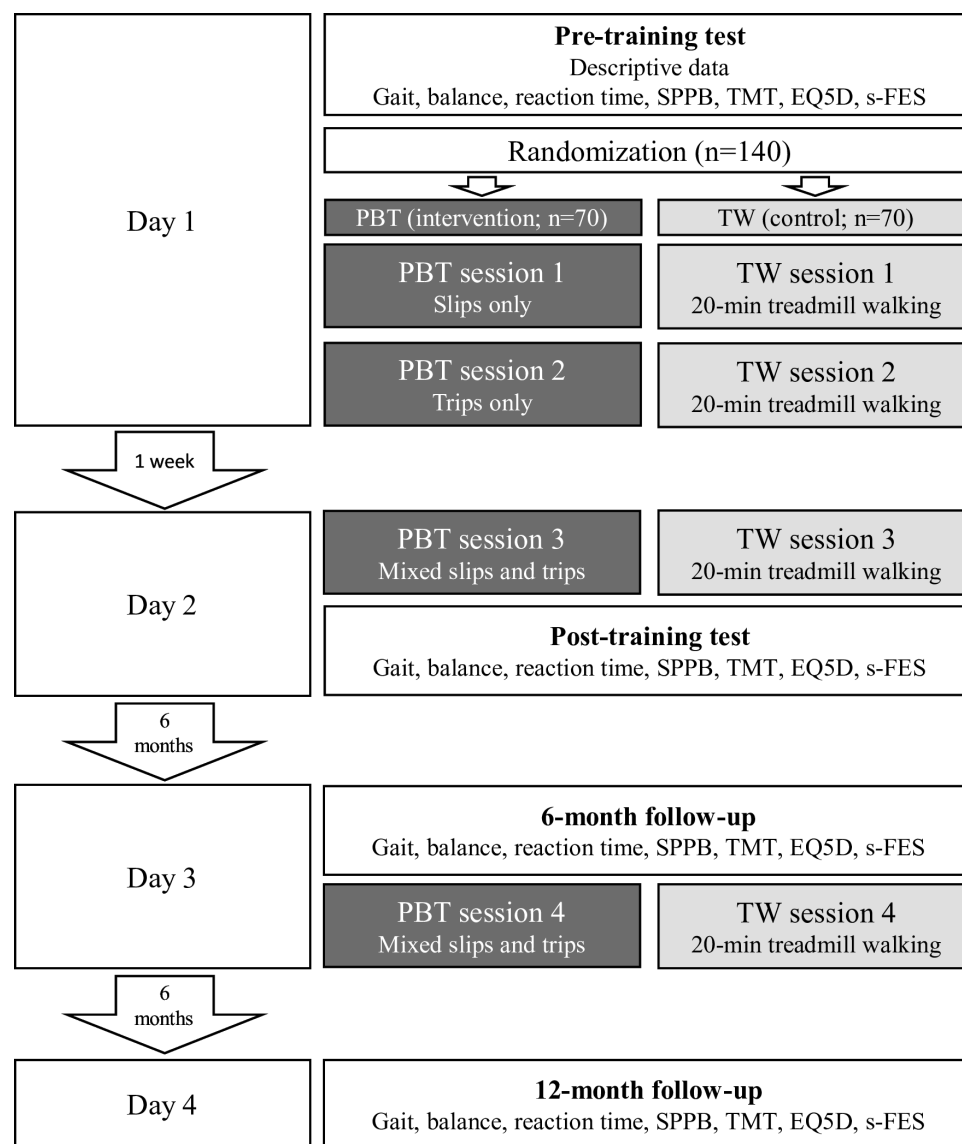


Figure 1 The study design. Dark grey boxes show the flow of the PBT group. Light grey boxes show the flow of the control group. White boxes indicate that all participants were assigned. EQ5D, EuroQoL 5-dimensions, 5-levels; PBT, Perturbation-based balance training; s-FES, Short falls efficacy scale; SPPB, Short physical performance battery; TMT, Trial making test; TW, Treadmill walking.

progressively increasing duration for the slips and acceleration for the trips. After every fourth perturbation, participants rated the perceived anxiety and difficulty of the previous perturbations on a scale from 1 to 5, with a higher score indicating higher perceived anxiety and difficulty. The intensity was increased if three criteria were fulfilled: (1) the combined perceived anxiety and difficulty were rated four or less, (2) the participant successfully recovered from the four prior perturbations and (3) the participant was willing to increase the difficulty. If any criteria were violated, the training intensity would remain at the highest tolerable level.

Treadmill walking training (control)

Participants allocated to the treadmill walking group walked for 20 min at their preferred walking speed,

matching the time spent on the treadmill by the PBT group.

Outcomes

This study reports preplanned secondary outcomes, including physical, cognitive and sociopsychological measures collected at the pretraining, post-training, 6-month follow-up and 12-month follow-up test (see figure 1). All outcomes were assessed by the same researcher, who was not blinded for group allocation. A detailed description of the tests and the instructions provided is available in online supplemental material 1.

The physical outcomes are all associated with fall risk and include single and dual-task gait, single and dual-task static balance, choice stepping reaction time and lower extremity performance.^{33–38} The gait assessment

consisted of three single-task and three dual-task trials of 8 m walking at a preferred walking speed, with the middle 6 m timed using a handheld stopwatch.^{37 39 40} As the dual-task, the participants were instructed to count backwards in threes from a random three-digit number. No instructions to either prioritise the walking or counting task were provided. The average gait speed of the three trials was used in the analyses. The balance assessment was conducted on a Wii balance board using the FysioMeter software (FysioMeter, V.1.2.1.4, Denmark).^{41–43} Participants were instructed to stand as still as possible for 30 s, three times as a single-task and three times as a dual-task. The dual-task involved naming items from specific grocery store sections (dairy, produce and butchery), with no instruction to focus on the balance or cognitive task. The average centre of pressure displacement area and speed from the three trials were used in the analysis. The choice stepping reaction test was also conducted using the Wii balance board and involved reacting as fast as possible to visual clues given on a computer screen by tapping the foot on the correct side of the Wii balance board.^{34 44} Seven reactions were collected, and the average reaction time of the initial six was used in the analyses. The Short Physical Performance Battery was used to evaluate lower extremity performance and involved three elements: (1) balance with three different foot positions (side-by-side, semitandem and tandem), (2) two 4 m walks and (3) five sit-to-stands.^{36 45} A score was calculated (range: 0–12; higher score indicates better performance) and used in the analyses. Further, the time used in the five sit-to-stands was also analysed as a measure of functional strength.⁴⁶

Cognitive function, known as executive function, was evaluated using the trail making test (TMT) part A and part B.^{47 48} Participants sequentially connected numbers (part A) or alternating numbers and letters (part B). Part A assessed visual search, motor speed skills and attention while part B evaluated working memory and task shifting.⁴⁸ The time to complete part B minus part A (Δ TMT) was used in the analyses.^{49 50}

Sociopsychological outcomes included concerns about falling and health-related quality of life. The concerns about falling were evaluated using the Short Falls Efficacy Scale-International, and the score was used in the analyses (range: 7–28; a higher score indicates higher concern).⁵¹ Moreover, the health-related quality of life was assessed using EuroQoL 5-dimensions, 5-levels (EQ-5D-5L).^{52 53} The EQ-5D-5L index score (range: –1 to 1; higher index indicates better quality of life) and Visual Analogue Scale score (range: 0–100; higher score indicates better quality of life) were used in the analyses.

Sample size

The sample size was calculated based on an expected decrease in the study's primary outcome in fall rates. Therefore, the sample size calculation was based on Poisson's regression model in G*Power (V.3.1.9.4, University of Kiel, Kiel, German). An expected 50% effect size from a base fall rate of 0.85 with an 80% power and 5%

significance level necessitated 70 participants in each group, assuming a 20% drop-out.

Randomisation

Immediately after pretraining assessments, participants were allocated to either the PBT or control group using a blocked randomisation module generated in STATA and uploaded in REDCap. The module was created by research staff not involved in any other trial activities. Random block sizes of 2, 4, 6 and 8 were used to conceal the allocation sequence. The nature of training interventions and practical limitations led to neither the participant nor the outcome assessor being blinded for group allocation.

Statistical methods

All statistical analyses were conducted following the preregistered statistical analysis plan in collaboration with an external biostatistician.³⁰ The primary statistical analyses were performed following the intention-to-treat principle. A per-protocol analysis was conducted for participants who completed at least 75% of the intervention. The analyses were conducted in STATA (V.17.0, StataCorp), and p values of <0.05 were considered statistically significant.

Demographic data are presented as a mean and SD, median and IQR, or number and percentage, where appropriate. A linear mixed-effects regression model with the Restricted Maximum Likelihood estimation procedure was used to evaluate the between-group differences in the physical, cognitive and sociopsychological measures. In the model, group and time were set as fixed and included together with the interaction term. Record ID was set as a random effect. The results will be presented as estimates of the between-group differences of the within-group changes (pretraining to post-training, pretraining to 6 months, and pretraining to 12 months). Model assumptions were checked by inspection of residual plots, and deviations will be mentioned, but will not affect the analysis. Further, missing data were appraised missing at random; thus, multiple imputations were not conducted as it does not add any benefits to the linear mixed-effects model.⁵⁴ We did not correct for multiple adjustments; thus, the results should be interpreted as explorative.⁵⁵

Patient and public involvement

Patients or the public were not involved in the design, or conduct, or reporting, or dissemination plans of our research.

RESULTS

Participant flow

Of the 199 screened older adults, 140 were enrolled and randomised to either the PBT or control group between March and November 2021 (see figure 2). The baseline characteristics of both groups can be found in table 1. Loss

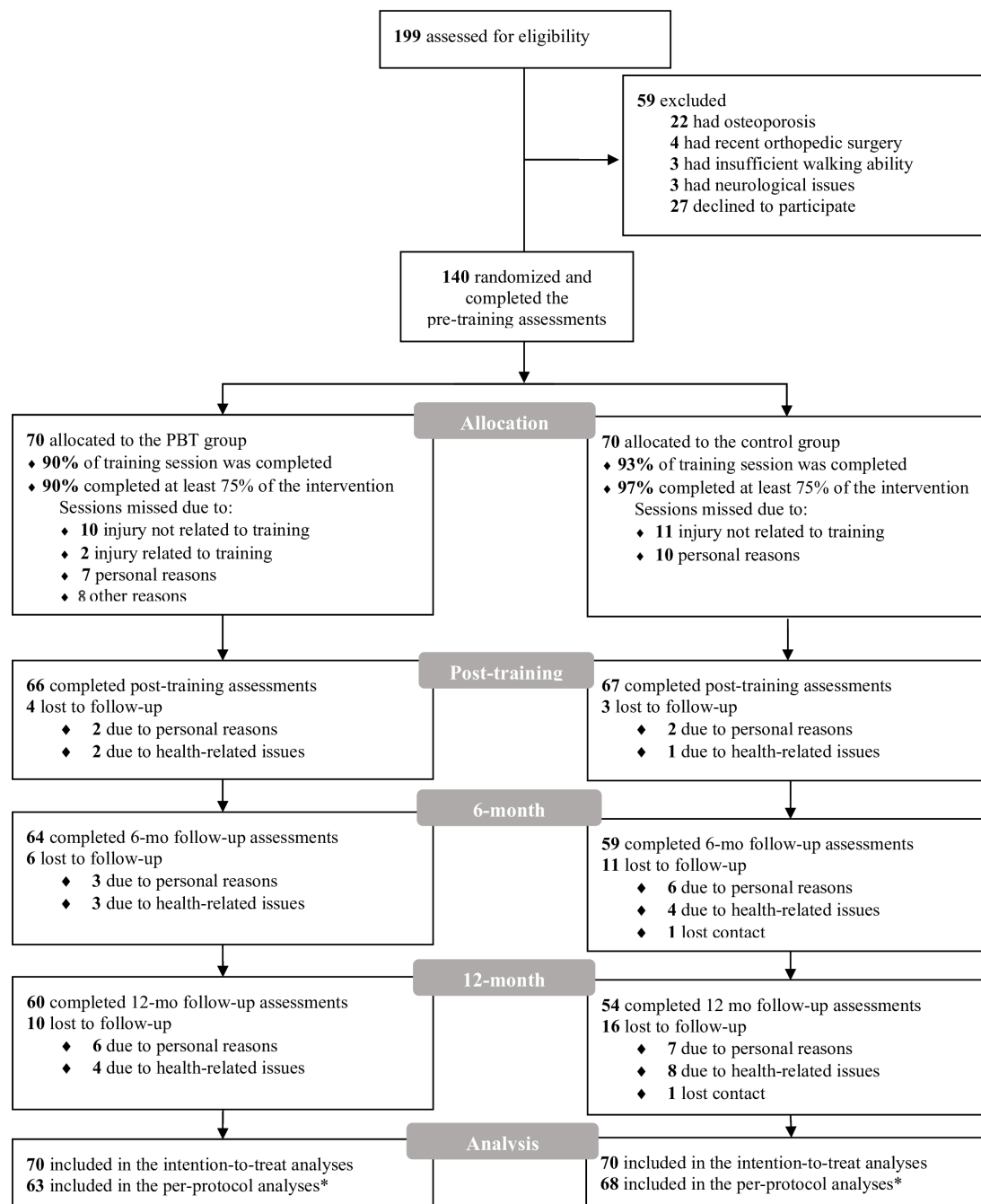


Figure 2 CONSORT flow chart of the participant flow through the present study. *Per-protocol analysis only included participants that completed at least 75% (three of four sessions) of the assigned intervention.

to follow-up was 4 (6%) and 3 (4%) at the post-training test, 6 (9%) and 11 (16%) at the 26-week follow-up, and 10 (14%) and 16 (23%) at the 52-week follow-up in the PBT and control group, respectively. At least one data point was missing for 13 (19%) in the PBT group and 18 (26%) in the control group. There were similar reasons for drop-out and demographic characteristics between groups among participants with missing data (see online supplemental material 2). The PBT group had a 90% adherence to training while the control group completed 93% of the assigned sessions. Moreover, 90% of the PBT group and 97% of the control group completed at least

75% of the intervention, which was the limit for being included in the per-protocol analyses.

Outcomes and estimation

All results from the unadjusted model regarding the physical, cognitive and sociopsychological measures are presented in online supplemental table 1. Multiple within-group differences were found; however, this section only contains the results of the between-group differences. Among the physical functions, a significant difference from the pre-training to post-training test favouring the PBT group was found in choice stepping

Table 1 Baseline characteristics of participants

	PBT group (n=70)	Control group (n=70)
Age (years), mean (SD)	72.7 (4.7)	72.0 (4.7)
Sex, no. female (%)	41 (59)	38 (54)
Frailty,* median (IQR)	2 (1–3)	2 (1–3)
Living arrangement, no. living alone (%)	23 (33)	24 (34)
Daily activity level, sitting down† (hours)	4 (6)	6 (9)
Medication, median (IQR)	2 (0–4)	3 (0–4)
Function of daily activities,‡ median (IQR)	2 (1–2)	2 (1–2)
Fall within the past 12 months, no. fall (%)	28 (40)	29 (41)
Cognition,§ median (IQR)	26 (24–28)	26 (24–28)
Physical function,¶ median (IQR)	12 (11–12)	12 (11–12)
Habitual gait speed (m/s), mean (SD)	1.3 (0.2)	1.3 (0.2)
Executive function,** median (IQR)	47.3 (26.1–63.5)	40.7 (29.1–61.8)

*Tilburg Frailty indicator (score 0–15; lower is better).

†International Physical Activity Questionnaire—time spent sitting down on average per day.

‡The Vulnerable Elderly-13 Survey (score 0–10; lower is better).

§The Short Orientation-Memory-Concentration Test (score 0–28; higher is better).

¶The Short Physical Performance Battery (0–12; higher is better).

**Trail Making Test part A subtracted from part B (lower score implied better performance).

PBT, perturbation-based balance training.

reaction time (–49 ms, 95% CI –80 to –18) and dual-task gait speed (0.05 m/s, 95% CI 0.01 to 0.09). However, none of these improvements were retained for the 6- or 12-months follow-up. There were no significant between-group differences in any of the other physical, cognitive or sociopsychological factors.

Ancillary analyses

When adjusting for age, sex and previous falls, the analyses identified significant changes from the pre-training to post-training test favouring the PBT group in single-task gait speed (0.03 m/s, 95% CI 0.00 to 0.06) and five sit-to-stands (–0.54s, 95% CI –0.97 to –0.01). Otherwise, the analyses led to similar results as the unadjusted model. Lastly, analysing the data using a per-protocol approach did not lead to different estimates than the intention-to-treat analyses. All results of the sensitivity analyses can be found in online supplemental material 3.

DISCUSSION

This secondary analysis from a randomised, controlled trial showed that four sessions of treadmill PBT did not lead to long-term (≥6 months) improvements in the evaluated physical, cognitive or sociopsychological measures. However, there was a significant short-term improvement from the pretraining to post-training test in choice stepping reaction time and dual-task gait speed favouring the PBT group.

Short-term effects of PBT

PBT led to significantly greater improvements in the choice stepping reaction time from pretraining to

post-training than regular treadmill walking (–49 ms, 95% CI –80 to –18). Choice stepping reaction time is a composite measure of fall risk that evaluates the ability to make quick and appropriate voluntary stepping responses to visual cues.³⁴ The improvement found in our study contrasts with,⁵⁶ which showed that three slip and trip overground walkway PBT sessions had no beneficial effects on the choice stepping reaction time.⁵⁶ This discrepancy may be due to Okubo *et al* having four stepping options in the reaction test while our test only had two.⁵⁶ This may lead to the performance being more reliant on executive functions, which this and previous PBT studies have shown limited effects on.⁵⁷ However, in line with our results, Kurz *et al* showed treadmill PBT significantly improved voluntary step execution onto one of two targets triggered by a somatosensory cue.⁵⁸ This improvement in voluntary step execution was achieved by a faster step initiation time which implies an enhanced central processing speed.⁵⁸ Furthermore, other PBT studies have also reported significant improvements in stepping reactions following either somatosensory or auditory cues.^{59–61} Our study, however, is the first to show that PBT improves voluntary stepping performance to visual cues. Collectively, PBT may induce adaptations within the central nervous system that benefit gait adaptability, which is important in fall prevention.⁶² Still, while there is no established minimally clinically important difference regarding choice stepping reaction time, the 7% improvement after PBT is smaller than the 13% difference previously found between fallers and non-fallers.³⁴

Our results also identified significant improvements from the pretraining to post-training test favouring PBT

in dual-task gait speed (0.05 m/s, 95% CI 0.01 to 0.09); yet, these improvements were below the limit of minimal clinically important difference (gait speed: 0.10 m/s).^{63 64} No other physical and cognitive measures showed a between-group difference following PBT. Supporting these findings, studies applying multidirectional perturbations within 3–5 sessions showed no improvements in physical measures of strength, static balance and gait.^{23 56 65} Likewise, a single session of 96 waist pull perturbations on a treadmill did not lead to changes in the executive function evaluated using the TMT.⁵⁷ However, in contrast to our results, studies including longer training intervention (≥ 4 weeks) in community-dwelling older adults and Parkinson's patients have been able to show improvements in various physical, cognitive and sociopsychological measures.^{25 27 28} In summary, our results indicate that adaptations to PBT interventions are highly task-specific, but some research may imply that higher dosages could lead to better transfer effects.^{13 14 18}

Lastly, the PBT intervention failed to show significant between-group differences in the sociopsychological measures. However, close-to-perfect concerns about falling and quality of life scores at pretraining enforced a ceiling effect leaving almost no room for improvement. Therefore, future studies should evaluate these parameters in participants exposed to substantial concerns about falling and low quality of life.

Long-term effects of PBT

A key component of PBT is the well-documented long-term retention of reactive balance adaptations following even small training dosages.^{18–20} Improvements in choice stepping reaction time must also be retained throughout the detraining period to be relevant. While choice stepping reaction time in the PBT group remained significantly lower at the 6 and 12 months follow-up compared with the pretraining test, these improvements were not significantly different from the control group (see online supplemental table 1). Thus, there were no long-term effects of PBT on any physical, cognitive or sociopsychological measures. These results align with our primary findings that PBT did not lead to a significant decrease in daily life fall rate.³¹ Our findings also support the current detraining literature, which points to a decline in physical performance following training cessation in older adults.^{66–68}

Practical implications

While the previously published results of the primary outcome paper showed a sustained improvement in reactive balance control over 12 months in laboratory settings (–63% laboratory fall rate at the 12-month follow-up), we only identified a partial transfer of adaptations to daily life (a nonsignificant 22% decrease in fall rates).³¹ Moreover, the findings reported in this paper also show that PBT may have limited effects on other important physical, cognitive and sociopsychological factors. This indicates that PBT should not be regarded as a single intervention but as

part of a multicomponent training programme. Considering the task-specificity of training adaptations, it is not surprising that multicomponent training programmes have proven most effective in improving overall physical and cognitive functions.^{69 70} It has recently been recommended that fall preventive training programmes should include balance challenging and functional exercises with additional tai chi and progressive strength training.⁷ Adding PBT to multicomponent training programmes could potentially improve the fall preventive effect with only slightly higher training dosages.^{13 18 62} However, this remains speculative until studies have shown the effectiveness of such multicomponent interventions.

Limitations

The results of this study should be interpreted considering the study's limitations. First, due to practical limitations and the nature of training interventions, the outcome assessor of these secondary outcomes and participants were not blinded for group allocation. Second, participants were convenience sampled, low-risk older adults with no specific physical, cognitive or sociopsychological problems. They were, therefore, not the targeted population for fall preventive training according to the recent world guidelines of fall prevention and management in older adults.⁷ Moreover, this population may have a limited potential for improvement, possibly explaining the lack of effect. Future PBT studies should investigate a frailer population to evaluate the potential effect among those prone to fall-related injuries. Finally, we did not correct for multiple comparisons, which may have led to false positive results due to mass significance; thus, the results should be seen as explorative only.

CONCLUSION

Secondary analyses from a randomised controlled trial showed that PBT led to short-term improvements in choice stepping reaction time and dual-task walking speed. However, these improvements were not retained at the 6 or 12 months follow-up tests. Moreover, PBT did not cause clinically important improvements in the other evaluated physical, cognitive or sociopsychological measures. These findings underline that adaptations to physical exercise are task-specific. However, the healthy state of the study's population may have imposed a ceiling effect limiting the ability to show any beneficial effects. Further studies adding PBT to multicomponent training programmes and studies on more frail older adults with a greater potential for improvements are needed.

Author affiliations

¹Department of Geriatric Medicine, Aalborg University Hospital, Aalborg, Denmark

²Department of Clinical Medicine, Aalborg Universitet, Aalborg, Denmark

³Department of Geriatric Medicine, Odense University Hospital, Odense, Denmark

⁴Department of Clinical Research, University of Southern Denmark, Odense, Denmark

⁵Department of Occupational Therapy and Physiotherapy, Aalborg University Hospital, Aalborg, Denmark

⁶Department of Health, Science and Technology, Aalborg University, Aalborg, Denmark

⁷Aalborg Health and Rehabilitation Center, Aalborg Municipality, Aalborg, Denmark

⁸Department of Materials and Production, Aalborg University, Aalborg, Denmark

X Jens Eg Nørgaard @JensEgNorgaard and Mathias Brix Brix Danielsen @MB_Danielsen

Acknowledgements We thank all the volunteering participants for committing to making this study possible. Further, we would like to thank Statistien Regitze Gyldenholm Skals for helping in analysing the data.

Contributors Concept and design: JEN, MGJ, JR, AJTS, JA, MBBD, AdSCO and SA. Acquisition: JEN. Drafting of manuscript: JEN. Critical revision of the manuscript for important intellectual content: MGJ, SA, MBBD, JR, AJTS, JA and AdSCO. Statistical analysis: JEN. Obtained funding: MGJ and SA. Administrative, technical or material support: JEN and AJTS. Supervision: JEN and MGJ. Final approval of manuscript: JEN, MGJ, SA, MBBD, JR, AJTS and JA. JEN is the guarantor.

Funding The Department of Geriatric Medicine, Aalborg University Hospital, Department of Clinical Medicine, Aalborg University and Aalborg Municipality funded the study (grant no. N/A).

Disclaimer The study funders had no role in the design and conduct of the study; collection, management, analysis and interpretation of the data; preparation, review, or approval of the manuscript; or decision to submit the manuscript for publication.

Competing interests None declared.

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

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

Ethics approval This study involves human participants and the study was performed following the Declaration of Helsinki. North Denmark Region Committee on Human Research Ethics (N-20200089) and the Danish Data Protection Agency (2021-014) approved the study. All participants gave written informed consent before enrolment. Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request. Deidentified trial results data will be available on reasonable request for non-commercial use up to 5 years after the publication of the trial findings. The available data will include (but is not limited to) deidentified individual participant data, the study protocol, the Statistical Analysis Plan (SAP), informed consent forms and analytic codes used. Requests for access will be reviewed by a designated data access committee to ensure they are for non-commercial, scientific purposes and that requesters agree to abide by data protection protocols. Data-sharing agreements will be required. Please note that the data-sharing plan outlined in the trial registration is outdated and cannot be changed.

Supplemental material This content has been supplied by the author(s). It has not been vetted by BMJ Publishing Group Limited (BMJ) and may not have been peer-reviewed. Any opinions or recommendations discussed are solely those of the author(s) and are not endorsed by BMJ. BMJ disclaims all liability and responsibility arising from any reliance placed on the content. Where the content includes any translated material, BMJ does not warrant the accuracy and reliability of the translations (including but not limited to local regulations, clinical guidelines, terminology, drug names and drug dosages), and is not responsible for any error and/or omissions arising from translation and adaptation or otherwise.

Open access This is an open access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited, appropriate credit is given, any changes made indicated, and the use is non-commercial. See: <http://creativecommons.org/licenses/by-nc/4.0/>.

ORCID iDs

Jens Eg Nørgaard <http://orcid.org/0000-0002-5256-6108>

Stig Andersen <http://orcid.org/0000-0003-3632-5213>

Jesper Ryg <http://orcid.org/0000-0002-8641-3062>

Andrew James Thomas Stevenson <http://orcid.org/0000-0003-1045-4738>

Mathias Brix Brix Danielsen <http://orcid.org/0000-0001-7431-5257>

Martin Gronbech Jorgensen <http://orcid.org/0000-0002-3189-644X>

REFERENCES

- Manini T. Development of physical disability in older adults. *CAS* 2011;4:184–91.
- Peel NM, Peel NM. Epidemiology of falls in older age. *Can J Aging* 2011;30:7–19.
- London AJ, Cigolle CT, Ha J, et al. The epidemiologic data on falls, 1998–2010: more older Americans report falling. *JAMA Intern Med* 2015;175:443–5.
- Friedman SM, Munoz B, West SK, et al. Falls and fear of falling: which comes first? A longitudinal prediction model suggests strategies for primary and secondary prevention. *J Am Geriatr Soc* 2002;50:1329–35.
- Stenhagen M, Ekström H, Nordell E, et al. Accidental falls, health-related quality of life and life satisfaction: a prospective study of the general elderly population. *Arch Gerontol Geriatr* 2014;58:95–100.
- Heinrich S, Rapp K, Rissmann U, et al. Cost of falls in old age: a systematic review. *Osteoporos Int* 2010;21:891–902.
- Montero-Odasso M, van der Velde N, Martin FC, et al. World guidelines for falls prevention and management for older adults: a global initiative. *Age Ageing* 2022;51:1–36.
- Falck RS, Davis JC, Best JR, et al. Impact of exercise training on physical and cognitive function among older adults: a systematic review and meta-analysis. *Neurobiol Aging* 2019;79:119–30.
- Sherrington C, Fairhall N, Kwok W, et al. Evidence on physical activity and falls prevention for people aged 65+ years: systematic review to inform the WHO guidelines on physical activity and sedentary behaviour. *Int J Behav Nutr Phys Act* 2020;17:1–9.
- Lee H-C, Chang K-C, Tsauo J-Y, et al. Effects of a multifactorial fall prevention program on fall incidence and physical function in community-dwelling older adults with risk of falls. *Arch Phys Med Rehabil* 2013;94:606–15.
- Chou CH, Hwang CL, Wu YT. Effect of exercise on physical function, daily living activities, and quality of life in the frail older adults: a meta-analysis. *Arch Phys Med Rehabil* 2012;93:237–44.
- Buford TW, Anton SD, Clark DJ, et al. Optimizing the benefits of exercise on physical function in older adults. *PM R* 2014;6:528–43.
- Grabner MD, Crenshaw JR, Hurt CP, et al. Exercise-based fall prevention: can you be a bit more specific? *Exerc Sport Sci Rev* 2014;42:161–8.
- Giboin LS, Gruber M, Kramer A. Task-specificity of balance training. *Hum Mov Sci* 2015;44:22–31.
- Berg WP, Alessio HM, Mills EM, et al. Circumstances and consequences of falls in independent community-dwelling older adults. *Age Ageing* 1997;26:261–8.
- Talbot LA, Musiol RJ, Witham EK, et al. Falls in young, middle-aged and older community dwelling adults: perceived cause, environmental factors and injury. *BMC Public Health* 2005;5:1–9.
- Luukinen H, Herala M, Koski K, et al. Fracture risk associated with a fall according to type of fall among the elderly. *Osteoporos Int* 2000;11:631–4.
- McCrum C, Bhatt TS, Gerards MHG, et al. Perturbation-based balance training: principles, mechanisms and implementation in clinical practice. *Front Sports Act Living* 2022;4:1015394.
- Pai Y-C, Yang F, Bhatt T, et al. Learning from laboratory-induced falling: long-term motor retention among older adults. *Age (Dordr)* 2014;36:1367–76.
- Epro G, Mierau A, McCrum C, et al. Retention of gait stability improvements over 1.5 years in older adults: effects of perturbation exposure and triceps surae neuromuscular exercise. *J Neurophysiol* 2018;119:2229–40.
- Lee A, Bhatt T, Liu X, et al. Can treadmill slip-perturbation training reduce longer-term fall risk upon overground slip exposure? *J Appl Biomech* 2020;36:298–306.
- Pai Y-C, Bhatt T, Yang F, et al. Perturbation training can reduce community-dwelling older adults' annual fall risk: a randomized controlled trial. *J Gerontol A Biol Sci Med Sci* 2014;69:1586–94.
- Lurie JD, Zagaria AB, Ellis L, et al. Surface perturbation training to prevent falls in older adults: a highly pragmatic, randomized controlled trial. *Phys Ther* 2020;100:1153–62.
- Gerards MHG, McCrum C, Mansfield A, et al. Perturbation-based balance training for falls reduction among older adults: current evidence and implications for clinical practice. *Geriatr Gerontol Int* 2017;17:2294–303.
- Shen X, Mak MKY. Technology-assisted balance and gait training reduces falls in patients with Parkinson's disease: a randomized controlled trial with 12-month follow-up. *Neurorehabil Neural Repair* 2015;29:103–11.
- Unger J, Chan K, Lee JW, et al. The effect of perturbation-based balance training and conventional intensive balance training on reactive stepping ability in individuals with incomplete spinal

- cord injury or disease: a randomized clinical trial. *Front Neurol* 2021;12:620367.
- 27 Steib S, Klamroth S, Gaßner H, *et al.* Perturbation during treadmill training improves dynamic balance and gait in Parkinson's disease: a single-blind randomized controlled pilot trial. *Neurorehabil Neural Repair* 2017;31:758–68.
 - 28 Smania N, Corato E, Tinazzi M, *et al.* Effect of balance training on postural instability in patients with idiopathic Parkinson's disease. *Neurorehabil Neural Repair* 2010;24:826–34.
 - 29 Rieger MM, Papegaaij S, Steenbrink F, *et al.* Effects of perturbation-based treadmill training on balance performance, daily life gait, and falls in older adults: REACT randomized controlled trial. *Phys Ther* 2024;104:pzad136.
 - 30 Nørgaard JE, Andersen S, Ryg J, *et al.* Effects of treadmill slip and trip perturbation-based balance training on falls in community-dwelling older adults (STABILITY): study protocol for a randomised controlled trial. *BMJ Open* 2022;12:e052492.
 - 31 Nørgaard JE, Andersen S, Ryg J, *et al.* Effect of treadmill perturbation-based balance training on fall rates in community-dwelling older adults: a randomized clinical trial. *JAMA Netw Open* 2023;6:e238422.
 - 32 Schulz KF, Altman DG, Moher D, *et al.* CONSORT 2010 Statement: updated guidelines for reporting parallel group randomised trials. *BMC Med* 2010;8:18.
 - 33 Muir-Hunter SW, Wittwer JE. Dual-task testing to predict falls in community-dwelling older adults: a systematic review. *Physiotherapy* 2016;102:29–40.
 - 34 Lord SR, Fitzpatrick RC. Choice stepping reaction time: a composite measure of falls risk in older people. *J Gerontol A Biol Sci Med Sci* 2001;56:M627–32.
 - 35 Johansson J, Nordström A, Gustafson Y, *et al.* Increased postural sway during quiet stance as a risk factor for prospective falls in community-dwelling elderly individuals. *Age Ageing* 2017;46:964–70.
 - 36 Veronese N, Bolzetta F, Toffanello ED, *et al.* Association between short physical performance battery and falls in older people: the progetto Veneto anziani study. *Rejuvenation Res* 2014;17:276–84.
 - 37 Cullen S, Montero-Odasso M, Bherer L, *et al.* Guidelines for gait assessments in the Canadian consortium on neurodegeneration in aging (CCNA). *Can Geriatr J* 2018;21:157–65.
 - 38 Montero-Odasso M, Almeida QJ, Bherer L, *et al.* Consensus on shared measures of mobility and cognition: from the Canadian consortium on neurodegeneration in aging (CCNA). *J Gerontol A Biol Sci Med Sci* 2019;74:897–909.
 - 39 Montero-Odasso M, Sarquis-Adamson Y, Kamkar N, *et al.* Dual-task gait speed assessments with an electronic walkway and a stopwatch in older adults: a reliability study. *Exp Gerontol* 2020;142:111102.
 - 40 Lyons JG, Heeren T, Stuver SO, *et al.* Assessing the agreement between 3-meter and 6-meter walk tests in 136 community-dwelling older adults. *J Aging Health* 2015;27:594–605.
 - 41 Clark RA, Mentiplay BF, Pua Y-H, *et al.* Reliability and validity of the Wii Balance Board for assessment of standing balance: a systematic review. *Gait Posture* 2018;61:40–54.
 - 42 Jorgensen MG, Laessoe U, Hendriksen C, *et al.* Intra-rater reproducibility and validity of Nintendo Wii balance testing in community-dwelling older adults. *Eur Geriatr Med* 2013;4:S87.
 - 43 Bonnechère B, Van Hove O, Jansen B, *et al.* Validation of the Wii Balance Board to assess static balance during dual-task activity in healthy subjects. *Med Novel Technol Devices* 2019;1:100003.
 - 44 Jorgensen MG, Paramanathan S, Ryg J, *et al.* Novel use of the Nintendo Wii board as a measure of reaction time: a study of reproducibility in older and younger adults. *BMC Geriatr* 2015;15:80.
 - 45 Freire AN, Guerra RO, Alvarado B, *et al.* Validity and reliability of the short physical performance battery in two diverse older adult populations in Quebec and Brazil. *J Aging Health* 2012;24:863–78.
 - 46 Goldberg A, Chavis M, Watkins J, *et al.* The five-times-sit-to-stand test: validity, reliability and detectable change in older females. *Aging Clin Exp Res* 2012;24:339–44.
 - 47 Gullikson T. Review of a compendium of neuropsychological tests: administration, norms, and commentary. *Contemp Psychol* 1992;37:385.
 - 48 Montero-odasso M. *Falls and Cognition in Older Persons*. Cham: Springer International Publishing, 2020. Available: <https://doi.org/10.1007/978-3-030-24233-6>
 - 49 Delbaere K, Close JCT, Heim J, *et al.* A multifactorial approach to understanding fall risk in older people. *J Am Geriatr Soc* 2010;58:1679–85.
 - 50 Lezak M, Howieson D, Loring D. *Neuropsychological Assessment*. 4th Ed. New York: Oxford University Press, inc, 2004.
 - 51 Marques-Vieira CMA, Sousa LMM, Severino S, *et al.* Cross-cultural validation of the falls efficacy scale international in elderly: systematic literature review. *J Clin Gerontol Geriatr* 2016;7:72–6.
 - 52 Sørensen J, Davidsen M, Gudex C, *et al.* Danish EQ-5D population norms. *Scand J Public Health* 2009;37:467–74.
 - 53 Feng Y-S, Kohlmann T, Janssen MF, *et al.* Psychometric properties of the EQ-5D-5L: a systematic review of the literature. *Qual Life Res* 2021;30:647–73.
 - 54 Peters SAE, Bots ML, den Ruijter HM, *et al.* Multiple imputation of missing repeated outcome measurements did not add to linear mixed-effects models. *J Clin Epidemiol* 2012;65:686–95.
 - 55 Rothman KJ. No adjustments are needed for multiple comparisons. *Epidemiology (Sunnyvale)* 1990;1:43–6.
 - 56 Okubo Y, Sturnieks DL, Brodie MA, *et al.* Effect of reactive balance training involving repeated slips and trips on balance recovery among older adults: a blinded randomized controlled trial. *J Gerontol A Biol Sci Med Sci* 2019;74:1489–96.
 - 57 Martelli D, Vashista V, Micera S, *et al.* Direction-dependent adaptation of dynamic gait stability following Waist-Pull Perturbations. *IEEE Trans Neural Syst Rehabil Eng* 2016;24:1304–13.
 - 58 Kurz I, Gimmon Y, Shapiro A, *et al.* Unexpected perturbations training improves balance control and voluntary stepping times in older adults - a double blind randomized control trial. *BMC Geriatr* 2016;16:58.
 - 59 Mansfield A, Peters AL, Liu BA, *et al.* Effect of a perturbation-based balance training program on compensatory stepping and grasping reactions in older adults: a randomized controlled trial. *Phys Ther* 2010;90:476–91.
 - 60 Parijat P, Lockhart TE. Effects of moveable platform training in preventing slip-induced falls in older adults. *Ann Biomed Eng* 2012;40:1111–21.
 - 61 Shimada H, Obuchi S, Furuta T, *et al.* New intervention program for preventing falls among frail elderly people: the effects of perturbed walking exercise using a bilateral separated treadmill. *Am J Phys Med Rehabil* 2004;83:493–9.
 - 62 Nørgaard JE, Jorgensen MG, Ryg J, *et al.* Effects of gait adaptability training on falls and fall-related fractures in older adults: a systematic review and meta-analysis. *Age Ageing* 2021;50:1914–24.
 - 63 Kwon S, Perera S, Pahor M, *et al.* What is a meaningful change in physical performance? Findings from a clinical trial in older adults (the LIFE-P study). *J Nutr Health Aging* 2009;13:538–44.
 - 64 Chui K, Hood E, Klima D. Meaningful change in walking speed. *Top Geriatr Rehabil* 2012;28:97–103.
 - 65 Allin LJ, Brolinson PG, Beach BM, *et al.* Perturbation-based balance training targeting both slip- and trip-induced falls among older adults: a randomized controlled trial. *BMC Geriatr* 2020;20:205.
 - 66 Blasco-Lafarga C, Cordellat A, Forte A, *et al.* Short and long-term trainability in older adults: training and detraining following two years of multicomponent cognitive—physical exercise training. *Int J Environ Res Public Health* 2020;17:5984.
 - 67 Fernández-García ÁI, Gómez-Cabello A, Gómez-Bruton A, *et al.* Effects of multicomponent training and detraining on the fitness of older adults with or at risk of frailty: results of a 10-month quasi-experimental study. *Eur J Sport Sci* 2023;23:1696–709.
 - 68 Vogler CM, Menant JC, Sherrington C, *et al.* Evidence of detraining after 12-week home-based exercise programs designed to reduce fall-risk factors in older people recently discharged from hospital. *Arch Phys Med Rehabil* 2012;93:1685–91.
 - 69 Giné-Garriga M, Roqué-Figuls M, Coll-Planas L, *et al.* Physical exercise interventions for improving performance-based measures of physical function in community-dwelling frail older adults. *Med Sci Sports Exerc* 2014;46:134.
 - 70 Schoene D, Valenzuela T, Lord SR, *et al.* The effect of interactive cognitive-motor training in reducing fall risk in older people: a systematic review. *BMC Geriatr* 2014;14:107.