A systematic review of the effects of perturbation training on preventing falls.

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ABSTRACT

Falls cause injury or death in healthy but frail older people. The efficacy of conventional falls prevention training for healthy older people may be sub-optimal, and perturbation training, a new approach that trains reflexive control of postural stability, has been evaluated in several trials. One systematic review of this new approach exists, but it included people with neurological diagnoses. The current systematic review aimed to evaluate if perturbation training can reduce falls in healthy frail older people and healthy young people. Included studies had to compare perturbation training to a control, in terms of falls incidence. Three separate protocols were devised for studies using different ages and falls outcomes. Sixteen eligible papers were found, comprising 849 participants. Perturbation training may be effective compared to no treatment in reducing laboratory-induced falls in older and younger people. Benefits may occur quickly, can be long-lived, and are generalisable. However, the efficacy of perturbation training in reducing community falls incidence in frail older people is uncertain. In all studies the quality of evidence is low to very low, and further rigorous research is required.

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Key Words: Falls, Falling, Perturbation, Trip, Slip, Prevention.

INTRODUCTION

Approximately one third of older people experience at least one fall per year (Shapiro & Melzer, 2010). Of these, about half will suffer two or more falls annually (Masud & Morris, 2001). Approximately 5% of falls lead to fractures (Masud & Morris, 2001; Rubenstein & Josephson, 2006), 20% of which are hip fractures (Masud & Morris, 2001) that carry a high probability of mortality (Rubenstein & Josephson, 2006).

During the last 30 years, conventional approaches to reducing falls in the healthy but frail older population have involved strength and power training of the lower extremities in combination with balance re-education. Unfortunately, published data have not shown a consistent benefit for such approaches (Orr, Raymond & Fiatarone, 2008). Although such methods may be able to reduce the incidence of falling compared to no treatment, there are still many people who fall despite these measures (Grabiner, Crenshaw, Hurt, Rosenblatt & Troy, 2014).

Part of the reason for the limited efficacy may be that conventional therapy tends to focus on training in a relatively stable standing position. This is at odds with the fact that after a trip or slip, which may be initiating factors in 60% (Blake et al.,1988; Luukinen, Herala, Koski, Honkanen, Laippala & Kivela, 2000) of all accidental falls, the person is rapidly moved into a far less stable posture before there is time for compensatory muscle activity to begin (Grabiner et al., 2014). Conventional methods may also not train the specific muscle synergies at sufficiently high velocities (Pijnappels, Bobbert & Van Dieen, 2005). In addition, the postural responses and recovery strategies triggered by a slip or trip are reflexive, and thus may not be specifically trained by voluntary exercise. Finally, conventional methods may not train 'feedforward' mechanisms of stability control. Theories of feedforward stability control suggest that the central nervous system (CNS) forms representations of stable limits of centre of gravity (COG) excursion relative to the base of support. These allow proactive adjustments to the velocity and trajectory of the COG during movement to decrease the likelihood that these limits will be crossed. This should reduce the probability of balance loss and the need for reactive responses (Pai & Iqbal 1999; Pai, Wening, Runtz, Iqbal & Pavol, 2003). In addition, even if balance loss does occur, such prior COG adjustments may allow successful reactive responses to be more easily achieved (Pai & Bhatt 2007). Only exposure to sudden unexpected shifts in the COG may refine CNS representation of safe COG limits, and thus improve the feedforward mechanism of stability (Pai et al., 2003).

This has led some researchers and clinicians to consider the efficacy of 'perturbation' training, which involves unexpected external perturbations during walking (Shapiro & Melzer, 2010) that mimic environmental slips and trips. Such training should develop feedforward mechanisms of stability control (Pai et al., 2003), as well as specifically training the rapid reactions required after a slip or trip has begun (Bhatt & Pai 2009a; Grabiner, Bareither, Gatts, Marone & Troy, 2012; Lurie, Zagaria, Pidgeon, Forman & Spratt, 2013).

Over the past 10 years much research has been published concerning perturbation training. This can be split into three main categories. The first concerns the effects of perturbation training on the incidence of community falls (those occurring in the natural setting) in older people (Lurie et al., 2013; Maki et al., 2013; Mansfield, Peters, Liu & Maki, 2010; Pai, Bhatt, Yang & Wang, 2014a; Rosenblatt, Marone & Grabiner, 2013).

The second category looks at the effects of perturbation training on the ability of older people to resist a simulated slip or trip in the laboratory (Grabiner et al., 2012; Parijat & Lockhart, 2012; Bhatt, Yang & Pai, 2012). This is clearly different from observing the effects on community falls, as the laboratory participants are 'primed' for the possibility of a fall and more completely focussed on the task, which may reduce the tendency to fall, supported by empirical evidence in older women (Pater, Rosenblatt & Grabiner, 2015). Moreover, the nature of simulated trips and slips in the laboratory may differ from perturbations encountered in the community. Nevertheless, Pai, Wang, Espy & Bhatt (2010a) have shown an association between the propensity to fall in the laboratory and the tendency to fall in the community, and so such studies may provide useful indirect evidence that can support evidence from the first category of research.

The third category concerns the effects of perturbation training on young healthy adults (Bhatt & Pai 2009a; Bhatt & Pai 2009b; Bhatt, Wang, Yang & Pai, 2013; Lee, Bhatt & Pai, 2016; Liu, Bhatt & Pai, 2016; Wang, Bhatt, Yang & Pai, 2011; Yang, Bart & Pai, 2013, Yang, Wang & Pai, 2014). Although the key aim of this review is to inform prevention of falls in older people, for whom falls are both prevalent and dangerous (Rubenstein & Josephson, 2006), data from younger people are also of relevance. Although younger people have greater strength and power, there is evidence that young and older people may respond to perturbation training at a similar rate (Pavol, Runtz, Edwards & Pai, 2002) and in a similar way (Pavol, Runtz & Pai, 2004). Furthermore, studies in younger people tend to experiment with different parameters of training, such as intensity and duration, and so conclusions from these may be used to inform training parameters in older adults. Inclusion of data on young people will therefore be of potential benefit to facilitate development of optimal treatment and research strategies aimed at reducing falls in older people.

Only one relevant systematic review currently exists. Mansfield, Wong, Bryce, Knorr & Patterson (2015) conducted a systematic review of eight randomised controlled trials (RCTs), evaluating the effectiveness of perturbation training in reducing community falls in older people. These authors showed a relative risk of falling of 0.71 (95% CIs: 0.52 to 0.96) if perturbation training was used, in comparison to other approaches. However, four of the RCTs comprised participants with neurological or orthopaedic diagnoses, and meta-analyses were not stratified or sub-grouped for such differing populations. It is possible that the meta-analysis may have overestimated the pooled magnitude of benefit, in relation to what might be expected in healthy frail older people, because the results in those with neurological conditions more strongly favoured perturbation training. Furthermore, an important recent RCT (Pai et al., 2014a) was not included. In contrast, the current review will be limited to healthy older and younger participants without diagnoses (such as stroke or amputation) that could be the cause of falling, because the tendency to respond to perturbation training and the underlying mechanism of postural instability are probably linked. This tallies with the views of Gillespie, Robertson, Gillespie, Sherrington, Gates, Clemson & Lamb (2012), who restricted their Cochrane meta-analysis on conventional fall prevention strategies to healthy frail older adults on the basis that people with neurological or other diagnosed conditions are likely to respond differently from frail healthy older adults.

The current systematic review contains three separate systematic review questions, each conforming to one of the three categories of research described above. These are:

1. Does perturbation training reduce community falls incidence compared to standard falls prevention treatment in healthy older people who are fallers or at risk of falling?
2. Does perturbation training reduce laboratory falls incidence compared to standard falls prevention treatment in healthy older people who are fallers or at risk of falling?
3. Does perturbation training reduce laboratory falls incidence compared to a comparison treatment in young healthy people?

METHODS

Study selection

The three protocols (Table 1) corresponding to the three review questions were developed by the authors through consensus. This was based on an initial survey of the literature, and discussion with clinicians who use perturbation training as part of their clinical practice. The following sections detail the protocol.

The protocols are also located online at: http://www.crd.york.ac.uk/PROSPERO/display_record.asp?ID=CRD42016039911 The online protocol was submitted after the initial searches had taken place, as a result of administrative delays.

Types of participants

For the two review questions looking at older people having 1) community falls or 2) laboratory falls, studies comprising adults with a mean age of >65 years were included, on the basis that falls begin to become much more prevalent after this age (Shapiro & Melzer, 2010). If studies comprised adults with a mean age between 55 and 65 years then these were included, but with a reduction in quality rating to reflect the 'indirectness' of such evidence to the specific review questions ('indirectness' refers to any departure in terms of the study PICO to the review protocol, and is explained fully in the 'quality assessment' section). Similarly, at least 50% of participants in a study needed to either have a history of at least one fall in the past year or be deemed at risk of falls by any appropriate criteria provided by study authors. If either of these conditions was not met then the study would again receive a reduction in quality rating. Participants had to be healthy (albeit frail) and studies were excluded if any participants had diagnosed conditions such as stroke or amputation that could cause falling. For the third research question, involving laboratory falls in younger people, any studies comprising healthy adults aged <55 years were included.

Types of intervention

For all three research questions, interventions had to comprise perturbation training, where sudden and unexpected anteroposterior or mediolateral forces were imposed on a treadmill, or on a walkway with moveable plates. Perturbation training could be given alone, or in combination with standard or other treatments.

Types of comparator

The key methodological criterion for inclusion was that studies had to have a comparator group. Any comparator was acceptable, non-active or active, as any comparator would help to eliminate intervening variables such as the placebo effect, practice effects or natural history effects as contributors to changes in the outcome. For the first and second research questions, the comparator would ideally be standard falls prevention treatment (such as lower limb strengthening and dynamic balance training), to permit interpretations of perturbation training efficacy compared to best available practice. If a non-standard treatment was used for the control group then a reduction in quality rating was applied for indirectness. For the third research question the comparator could be any treatment because established falls prevention treatments do not exist in young healthy people.

Types of outcome

For the first review question, the outcome was community falls, defined by the existence or not of at least one fall occurring outside the laboratory setting within a clearly defined time interval. For the second and third questions, the outcome was a laboratory-induced fall 'in harness', defined as a loss of balance during the laboratory falls test that exceeded a study-specified load on the safety harness load cell, or that caused an unambiguously unrecoverable loss of balance.

Types of study

For all three research questions randomised trials were preferred, but non-randomised trials were allowed, even though these would tend to have greater selection bias. Longitudinal observational approaches, such as prospective or retrospective cohort studies, or case-control studies, were not excluded as such studies would still enable some degree of causality to be established between training method and falls incidence. Cross-sectional studies were excluded as they would be unable to provide any evidence of causality.

Search

The search strategy was aimed at all three protocols. This aimed for maximal sensitivity at the expense of specificity by avoiding 'AND' terms. The key words were: *trip, trips, tripping, slip, slips, slipping, perturbation, perturbations, "perturbation-based balance training", platform, treadmill, "agility training", "dynamic balance training"* all linked by the term 'OR'. The databases used (in order of succession) were PubMed, EBSCOHost CINAHL, and EBSCOHost SportDiscus, and the last search date was 13/11/2016. All searches were limited to peer-reviewed journals and 'English' to facilitate retrieval and extraction of data. For PubMed, the search was also limited to 'controlled clinical trials' and 'humans', whilst for CINAHL the additional limiters were 'clinical trials' and 'humans'. For SportDiscus the limiters were 'academic journals' and 'articles'. The differing limiters used across databases were due to the differing limiters available within each database. No date limits were set as reviewers were uncertain of the time when perturbation training may have begun to be evaluated. Abstract selection was carried out by both authors and decisions on inclusion were based on consensus.

Data extraction and management

Data from the included papers were extracted onto pre-formatted forms by both authors independently, detailing study design, population, sample characteristics, intervention, comparator, results, conflicts of interest, risk of bias and indirectness. Consensus was used to decide on the final content of forms.

Synthesis of findings

For each of the three separate review questions, findings were synthesised from two or more studies, using fixed effects meta-analysis, when the population, interventions, comparators and outcomes (PICO) of studies were sufficiently similar to enable meaningful and useful pooling of results. If the PICO of different studies was sufficiently dissimilar to allow meta-analysis then a narrative synthesis was carried out. Where available, intention to treat data were used.

Stratification and sub-grouping

Stratification of studies prior to the meta-analysis was carried out as needed, according to the protocols (Table 1), on the grounds that the stratifying variables denoted plausible biological grounds to expect different results within each stratum. After subsequent stratified or non-stratified pooling of studies, further sub-grouping according to *a priori* strategies outlined in the protocols (Table 1) was carried out if serious heterogeneity was observed, shown by an $I^2>50\%$. If more than one sub-grouping strategy was listed in the protocol, then each sub-grouping strategy was used in order of priority, until heterogeneity was resolved, shown by heterogeneity being reduced to $I^2<50\%$ in all sub-groups. At this point results were reported for each sub-group separately, and the lower priority sub-grouping strategies were not used. If all sub-grouping strategies failed to resolve heterogeneity then no sub-grouping was carried out, and a random effects model was adopted to allow for the likelihood of a distribution of populations. Since the outcome of falling was a binary outcome, risk ratios (RR) were used where possible but Peto odds ratios were used if there was a low event rate in one of the groups. ReviewManager 5.3 © was used for meta-analyses.

Quality assessment

Quality assessment was performed according to the GRADE approach (Schünemann et al., 2006), and comprised the following:

1. Risk of bias

Each study was appraised for the risk of selection, performance, detection, attrition and outcome reporting bias for the chosen outcome. Based on these criteria, the overall risk of bias for each study was deemed *very serious* (score of -2), *serious* (-1) or *not serious* (0), based on a reasoned estimation of the overall effects of such bias. This was assessed for each study separately and then a weighted average of bias scores for the chosen outcome across all studies in the meta-analysis was calculated using the meta-analysis weightings (which were based on precision). If a meta-analysis had not been undertaken then a simple average of quality ratings would be given.

2. Indirectness

This concerned any discrepancies between the PICO of the systematic review question (Table 1) and the PICO of each included study. Indirectness was deemed *very serious* (-2), *serious* (-1) *or not serious* (0) for each study separately, depending on the number of discrepancies. An overall score for the outcome across all studies was then calculated (as for risk of bias).

Table 1: Protocol for the 3 research questions

Review questions	Does perturbation training reduce *community falls* incidence more than standard falls prevention treatment in healthy older people who are fallers or at risk of falling?	Does perturbation training reduce *laboratory falls* incidence more than a comparison treatment in healthy older people who are fallers or at risk of falling?	Does perturbation training reduce *laboratory falls* incidence more than a comparison treatment in young healthy people?
Population	• Older people aged 65 years upwards • Healthy - free from or any diagnosed condition that could lead to falls (e.g. stroke, amputation, total hip replacement, balance disorders) • Either deemed at risk of falling (frail) or single/frequent fallers. Reduce quality rating of studies in terms of 'indirectness' • If mean age was aged <65 but > 55 years • if >50% of participants were not fallers or were not deemed at risk of falling		Young people (aged <55 years). These need to be healthy and not frail or fallers.
Intervention	• Perturbation (slip/trip) training on treadmill or on a walkway with moveable plates Exclude any slip/trip training done on slippery surfaces Can be combined with or without standard falls prevention training		
Comparator	• Standard falls prevention training • Downgrade for indirectness if any other control intervention is used		• Any control intervention
Outcomes	Community falls frequency	"Falls in harness" on laboratory walkway or treadmill platform.	
Study types	Any randomised or non-randomised study which uses one or more comparison groups.		
Strata*/sub-groups**	Stratify by +/- inclusion of standard training with intervention Sub-group by • Comparator type • Single fallers/frequent fallers • Age (<80 vs >80)	Sub-group by Comparator type	Sub-group by Comparator type
Analysis plan	Meta-analysis if appropriate.		
Search plan	Pubmed, EBSCOHost CINAHL, EBSCOHost SportDiscus; key words: trip, trips, tripping, slip, slips, slipping, perturbation, perturbations, "perturbation-based balance training", platform, treadmill, "agility training", "dynamic balance training"		

*Strata denote categories for separate analyses/synthesis which are fixed *a priori*. Strata interact – thus 2 binary strata will lead to 4 sub-strata.
**Sub-groups denote categories for analysis/synthesis that are conditional upon statistical heterogeneity [I^2 > 50%] in meta-analysis. Sub-groups do not interact – each is examined separately

3. Inconsistency

If the outcome meta-analysis I^2 was <50% then a rating of non-serious inconsistency (score of 0) was given. If the outcome meta-analysis I^2 was ≥50% but <75% then a rating of serious inconsistency (score of -1) was given, and if the outcome meta-analysis I^2 was ≥75% then a rating of very serious inconsistency (score of -2) was given. Note that if sub-grouping managed to reduce heterogeneity then the results for each sub-group would be appraised as separate outcomes, each rated as having no serious inconsistency. If no meta-analysis had been undertaken then the level of inconsistency was determined based on an estimate of the differing effects.

4. Imprecision

Imprecision was based on the spread of the 95% confidence intervals (CI) of the pooled effect across arbitrary but established thresholds of clinical importance for the outcome. If the confidence intervals crossed the thresholds of a 25% reduction in risk and a 25% increase in risk (risk ratios [RR] of 0.75 and 1.25, and, by default, odds ratios [OR] of the same value) then a rating of very serious imprecision (score of -2) was given. If the confidence intervals crossed just one threshold then a rating of serious imprecision (score of -1) was given. If no thresholds were crossed by the confidence intervals then a rating of no serious imprecision (score of 0) was given. If no meta-analysis had been undertaken then the level of imprecision was determined based on an estimate of the separate effects.

Overall score

Scores from the four quality aspects were summed. If the overall score was -3 or less, then a rating of very low quality was given, if the overall score was -2 a rating of low quality was given, if the overall score was -1 then a moderate quality rating was assigned and if the overall score was 0 then a rating of high quality was given (Schünemann et al., 2006). These gradings were used to guide interpretation of results.

Since only one outcome (incidence of falling) is used in this review, if a study did not include this outcome then it would not be included. However excluded studies were perused to see if any had been excluded solely for the lack of a falls outcome. The plan was to evaluate such studies to assess if the falls outcome had been deliberately left out because it may have contradicted other outcomes or the favoured hypothesis. Assessment of possible publication bias was conducted using a funnel plot where meta-analyses had been undertaken with a minimum of 10 studies (Higgins & Green, 2011).

RESULTS

Included and excluded studies

The PubMed search yielded 5138 articles, from which 42 were obtained for further analysis. Subsequently, the CINAHL search yielded 790 articles, from which 2 previously unseen articles were obtained for further analysis. Finally, the SportDiscus search yielded 13,310 articles, which were deemed too many for preliminary selection. Hence for this search the original search strategy was combined with 'fall or stability or balance' using the AND operator. This reduced the yield to 1935 articles, from which 5 further articles were obtained for further analysis. Perusal of reference lists in retrieved papers yielded four extra articles, and these were also obtained for more detailed reading. Of these 53 articles, 16 met the inclusion criteria of any of the 3 protocols (Table 1) and were included in the review (Figure 1). Reasons for the exclusion of the other 37 articles are given in Table 2.

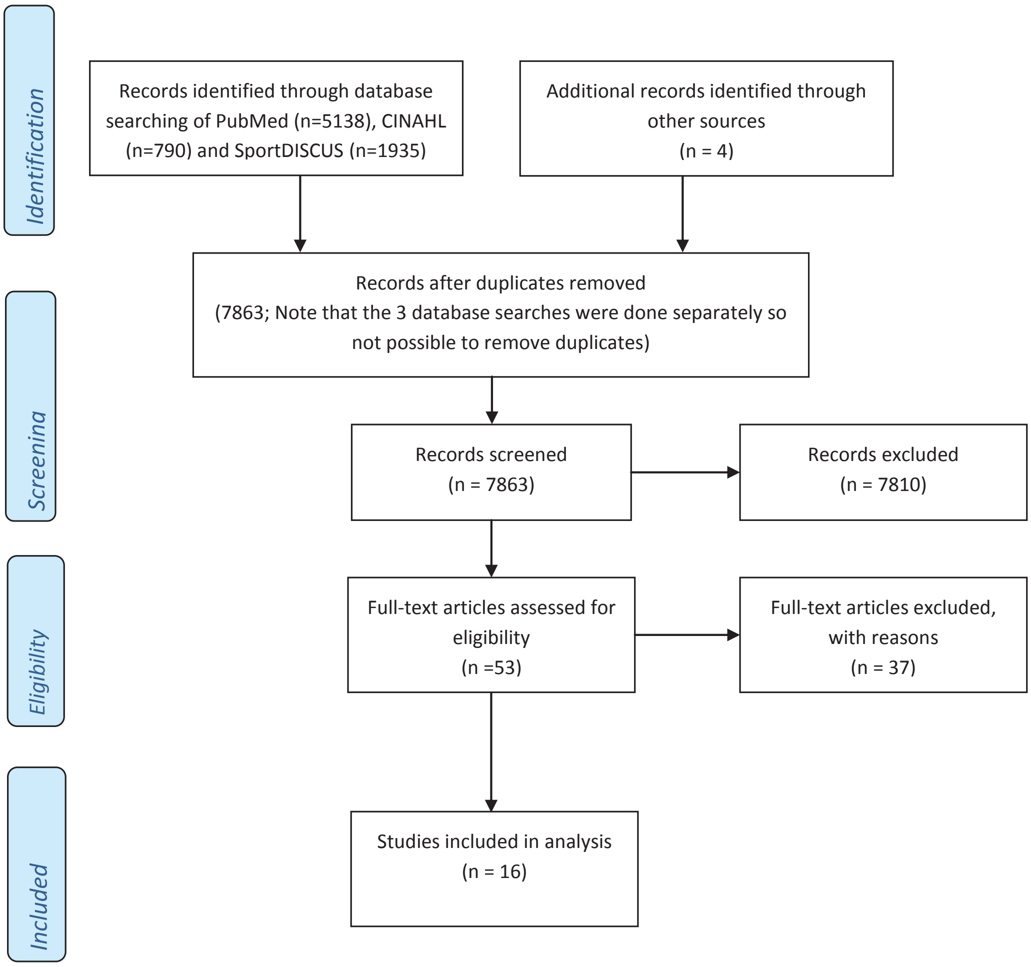

Figure 1: PRISMA Study Flow Diagram

Table 2: Excluded studies list

Study	Reason for exclusion
Bhatt & Pai, 2008	No control group
Bhatt et al., 2011	No control group
Bieryla et al., 2007	No falls data
Cham & Redfern 2001	Descriptive kinematic study
Dijkstra et al.,2015	No control group
Grabiner et al., 2014	Review
Han & Yang, 2015	Did not relate to perturbation training
Kim & Lockhart, 2010	Did not relate to perturbation training
Kojima et al., 2008	No control group
Kurz et al., 2016	No falls data
Lee et al., 2013	Did not relate to perturbation training
Lesinki et al., 2015	Review with no falls outcomes
Liu & Kim, 2012	No control group
McIlroy & Maki, 1996	No control group
Melzer & Oddison, 2013	No falls data
Oddsson et al., 2004	No control group
Pai et al., 2010b	No control group
Pai & Bhatt, 2007	Review
Pai et al., 2014b	No control group
Parijat et al., 2015a	Virtual reality study
Parijat et al., 2015b	Virtual reality study
Patel & Bhatt, 2015	No control group
Pater et al., 2015	No control group
Pavol et al., 2002	No control group
Pavol et al., 2004	No control group
Rossi et al., 2013	No falls outcomes
Sakai et al., 2008	No falls outcomes or control group
Sessoms et al., 2014	Participants were post amputation
Shapiro & Melzer, 2010	Descriptive account of the perturbation device
Shimada et al., 2004	50% had diagnoses such as Parkinson’s disease.
Shirota et al., 2014	Descriptive kinematic study
Sohn & Kim, 2015	Did not relate to perturbation training
Yang et al., 2011	No control group
Yang et al., 2009	No control group
Yang et al., 2012	Descriptive kinematic study
Yang & Pai,2013	No control group
Yang & Pai, 2011	Not evaluating interventions

1. Does perturbation training reduce community falls risk compared to standard falls prevention treatment in healthy older people who are fallers or at risk of falling?

Studies included

Five relevant studies (Lurie et al., 2013; Maki et al., 2013; Mansfield et al., 2010; Pai et al., 2014a; Rosenblatt et al., 2013) comprising 484 participants were found. Mean ages in the studies ranged from 65 to over 80 years, but mean ages were not always documented. Mansfield et al. (2010) contained >50% of fallers in the study, but no other studies were documented to contain >50% of fallers. Lurie et al. (2013) stated that participants were recruited as they were at risk of falling, but criteria were not described, and ‘risk of falling’ status was unclear in all other papers. These issues contributed to the serious/very serious risks of ‘indirectness’ described below.

For three studies (Maki et al., 2013; Mansfield et al., 2010; Rosenblatt et al., 2013) data on the numbers falling at follow up were not available in the published papers. However the systematic review by Mansfield et al. (2015) published the numbers falling in these studies, derived from communication with the study authors, and it is these falls data that have been included in the meta-analysis. Detailed study characteristics are given in Table 3.

Table 3: Characteristics of the studies for review question 1. All participants were protected by a harness during training

Study name and type	Sample characteristics	Intervention	Comparator	Outcome measure	Risk of bias	Indirectness
Lurie et al., 2013 RCT	64 healthy adults at risk of falls. Mean age c80 years. 50% female in perturbation group and 67% female in standard PT group.	Standard physiotherapy (see right) with addition of treadmill perturbation training. Trips or slips were applied, with magnitude of disturbances depending on patient ability. Parameters left to the discretion of the PT.	Standard physiotherapy comprising patient-specific strengthening, flexibility and dynamic balance exercises. Some given in clinic and some as home exercises. Parameters left to the discretion of the PT.	All-cause community falls, evaluated retrospectively by a 3 month phone call.	Very serious. No assessor blinding, and possible attrition and detection bias.	Serious. No information on baseline fallers / risk of falling.
Pai et al., 2014a RCT	212 adults aged 73.6 years. Baseline rates of community falling (for previous 12 months): 34% of intervention group; control: 39%.	24 unexpected slip perturbations while walking over a moving platform in a single session.	One unexpected slip perturbation while walking over the moving platform.	All cause community falls at 12 month follow up. Over the year falls were recorded in a falls diary, and a researcher would call each participant at 6-week intervals to obtain the diary details, and if a fall had occurred the participant would be interviewed.	Very serious. No allocation concealment, and no assessor blinding.	Very serious. <50% fallers, no information on risk of falling, and comparator not standard training.
Maki et al., 2013 Pilot RCT	8 aged 79-89 in perturbation group, and 69-86 in control group.	Perturbation training, done for 30 minutes, 3 times per week over 6 weeks.	Training of rapid volitional stepping and reaching movements.	Community falls. The data are derived from Mansfield et al., (2015), the authors of which had contacted Maki and colleagues for the falls data.	Very serious. No allocation concealment, and no assessor blinding.	Very serious. <50% fallers, no information on risk of falling, and comparator not standard training.
Rosenblatt et al., 2013 Pseudo-randomised	170 women of mean age 65. Baseline falls history: 38.8% in control group and 37.8% in perturbation group.	Four one hour sessions comprising large trip perturbations on a treadmill over 2 weeks.	No training	Community falls, collected via postcards or emails every 2 weeks for one year. The data for number of all-cause fallers per group was derived from Mansfield et al., (2015).	Very serious. Pseudo random alternate allocation, no assessor blinding and likely attrition bias.	Very serious. <50% fallers, no information on risk of falling, and comparator not standard training.

Study name and type	Sample characteristics	Intervention	Comparator	Outcome measure	Risk of bias	Indirectness
Mansfield et al., 2010 RCT	30 adults (aged 64-80 years). 23/30 had experienced at least one fall in the past 5 years.	6 week perturbation-based balance training program, conducted on a motion platform that could move in 4 different directions. At least 24 perturbations were related to stepping and at least 24 were related to grasping tasks.	6 week control program involving flexibility (2 days per week) and relaxation training (1 day per week).	Community falls. The data for number of all-cause fallers per group was derived from Mansfield et al., (2015).	Very serious. No allocation concealment, and no assessor blinding.	Very serious. <50% fallers, no information on risk of falling, and comparator not standard training.

Effects

The studies were stratified (as per protocol) into two groups according to whether studies had combined the perturbation training with standard training (Figure 2) or not. The study by Lurie et al. (2013), as the only study to have combined perturbation and standard training, was therefore analysed in a separate stratum. No serious heterogeneity was observed in either stratum, so sub-grouping was not carried out. Fixed effects meta-analysis showed uncertain effects for perturbation training in both strata. Relative to the comparator, in the stratum where perturbation training was combined with standard training there was a RR (95% CI) for falls of 0.62 (0.20 to 1.89), and in the stratum where perturbation training was given alone there was a RR (95% CI) for falls of 0.89 (0.70 to 1.12) (Figure 2).

Study or Subgroup	log[Risk Ratio]	SE	Weight	Risk Ratio IV, Fixed, 95% CI
7.1.2 Perturbation and standard training				
Lurie 2013	-0.4762	0.567	100.0%	0.62 [0.20, 1.89]
Subtotal (95% CI)			**100.0%**	**0.62 [0.20, 1.89]**
Heterogeneity: Not applicable				
Test for overall effect: Z = 0.84 (P = 0.40)				
7.1.3 Perturbation alone				
Maki 2008	-0.4055	0.5774	4.3%	0.67 [0.21, 2.07]
Mansfield 2010	0.1586	0.5664	4.5%	1.17 [0.39, 3.56]
Pai 2014	-0.6757	0.3017	15.9%	0.51 [0.28, 0.92]
Rosenblatt 2013	-0.0027	0.1388	75.2%	1.00 [0.76, 1.31]
Subtotal (95% CI)			**100.0%**	**0.89 [0.70, 1.12]**
Heterogeneity: Chi² = 4.59, df = 3 (P = 0.20); I² = 35%				
Test for overall effect: Z = 1.00 (P = 0.32)				
Test for subgroup differences: Chi² = 0.38, df = 1 (P = 0.54), I² = 0%				

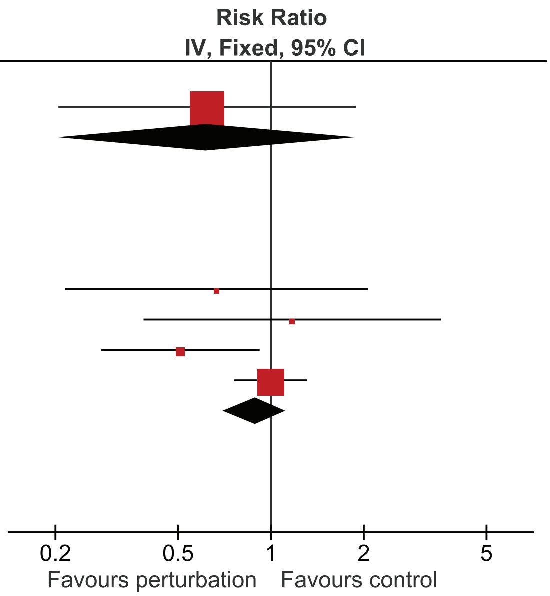

Figure 2: Forest plot for the effects of perturbation training compared to control on falls risk. The analysis was stratified by inclusion of standardised training with perturbation training or not. A generic inverse variance method has been used as the results by Lurie et al. 2013, adjusted for baseline falls incidence, were only available as a risk ratio.

Quality

Quality of the falls outcome in the perturbation-only stratum was deemed very low. This was due to very serious risk of bias, very serious indirectness and very serious imprecision across studies. Quality was also very low in the perturbation and standard training stratum for the same reasons, although indirectness was deemed serious rather than very serious. Details of all these quality issues are provided in Table 3 and the footnotes to Table 7.

2. Does perturbation training reduce laboratory falls risk compared to a comparison treatment in healthy older people who are fallers or at risk of falling?

Studies included

Three relevant studies were found, comprising 145 participants. Two (Grabiner et al., 2012; Parijat et al., 2012) compared the effects of perturbation training to no treatment, and one (Bhatt et al., 2012) compared the effects of perturbation training with a single extra 'top-up' treatment 3 months later to perturbation training without the 'top-up' treatment. Mean ages were above 70 years in both Parijat et al. (2012) and Bhatt et al. (2012), but in Grabiner et al. (2012) the control group had a mean age of <65 years. No study provided any evidence that the participants were fallers or were at risk of falling. Study details are given in Table 4.

Table 4: Characteristics of the studies for review question 2. All participants were protected by a harness during training

Study name and type	Sample characteristics	Intervention	Comparator	Outcome measure	Risk of bias	Indirectness
Parijat et al., 2012 RCT	24 adults aged 72.7 years, 12 of whom were female. At baseline all participants were exposed to a slip on a slippery surface: 5/12 fell in intervention group and 6/12 fell in control group.	Two weeks later, the intervention group experienced 12 simulated slips on a slippery moving force plate embedded on a 15m walkway. The slip trials were interspersed over 24 trials to reduce participant prediction of slips.	The control group had only normal walking trials, but the group were brought to the lab to maintain comparability.	One day post-training, the single slip test performed at baseline was repeated.	Very serious. No allocation concealment, and no assessor blinding.	Very serious. <50% fallers, no information on risk of falling, and comparator not standard training.
Grabiner et al., 2012 Pseudo-randomised	66 women aged 65.9 years (intervention) and 58.8 years (control).	Mean 142.5 perturbations in total over 4 weeks. The perturbations, made with the participant in a standing position, were exerted by a treadmill giving a sudden forward motion (simulating a trip). Magnitude varied according to participant performance.	No treatment	Existence of a fall, defined as loss of stability requiring 'unambiguous' harness protection, after a single mechanically induced trip on a walkway, undertaken about one week post training.	Very serious. Quasi-randomised with alternate allocation, no assessor blinding and probable attrition bias.	Very serious. <50% fallers, no information on risk of falling, comparator not standard training and control group aged 55-65 years.

Study name and type	Sample characteristics	Intervention	Comparator	Outcome measure	Risk of bias	Indirectness
Bhatt et al., 2012 RCT	Forty-eight adults aged 72.3 years. 35% had experienced prior community falls.	24 single session slip perturbations combined with an ancillary session of a single slip perturbation 3 months later. Slips during ambulation were induced by 2 moveable platforms placed on a 7m walkway.	The same 24 single session slip perturbations, without ancillary session.	At 6 months, the risk of falling was determined by the response to a single slip perturbation, with a fall defined as a slip where >30% body weight was detected by the harness load cell.	Very serious. No allocation concealment, and no assessor blinding.	Very serious. <50% fallers, no information on risk of falling, and comparator not standard training.

Effects

In the meta-analysis comprising the results of Grabiner et al. (2012) and Parijat et al. (2012), the pooled effect favouring perturbation training was statistically and clinically significant, with a Peto OR (95% CI) for falls of 0.18 (0.05 to 0.63) (Figure 3). Bhatt et al. (2012) did not provide clear data on falls rates, and so their data could not be included in the meta-analysis, but the authors stated that the difference in falls rates between groups was non-significant (p=0.5). The different effects may relate to the very active comparator used in Bhatt et al. (2012), which did not differ greatly from the intervention, in contrast to the inactive control treatments in the other two studies. It is worth noting that the risk ratio in both studies in the meta-analysis was similar despite Grabiner et al. (2012) employing trips as the training and testing perturbation, with Parijat et al. (2012) using slips instead.

Study or Subgroup	Perturbation Events	Perturbation Total	Control Events	Control Total	Weight	Peto Odds Ratio Peto, Fixed, 95% CI
Grabiner 2012	1	22	8	30	73.0%	0.22 [0.05, 0.93]
Parijat 2012	0	12	3	12	27.0%	0.11 [0.01, 1.19]
Total (95% CI)		**34**		**42**	**100.0%**	**0.18 [0.05, 0.63]**
Total events	1		11			

Heterogeneity: Chi² = 0.23, df = 1 (P = 0.63); I² = 0%
Test for overall effect: Z = 2.70 (P = 0.007)

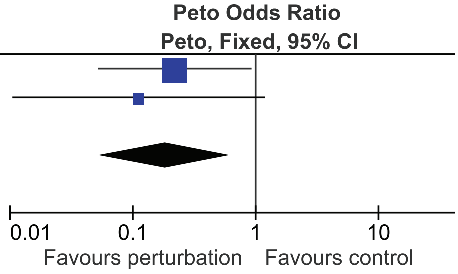

Figure 3: Forest plot for the effects of trip perturbation training compared to no perturbation training on odds of slip-induced laboratory falls in older participants

Quality

Quality of the falls outcomes in the meta-analysis was deemed very low. This was due to very serious risk of bias, and very serious indirectness. Quality was also very low for the single non-meta-analysed study (Bhatt et al., 2012) for the same reasons, as well as very serious imprecision suggested by the p value of 0.5. Details of all these quality issues are provided in Table 4 and the footnotes to Table 7.

3. Does perturbation training reduce laboratory falls risk compared to a comparison treatment in young healthy people?

Included studies

Eight eligible studies were found (Bhatt & Pai, 2009a; Bhatt & Pai, 2009b; Bhatt et al., 2013; Lee et al., 2016; Liu et al., 2016; Wang et al., 2011; Yang et al., 2013; Yang et al., 2014). All studies had ages that complied with the protocol, and all participants were healthy non-fallers. Six compared slip perturbation training to no treatment (Bhatt & Pai, 2009b; Bhatt & Pai, 2013; Lee et al., 2016; Wang et al., 2011; Yang et al., 2013; Yang et al., 2014) (Table 5) and two compared permutations of different intensities and/or frequencies of perturbation training to each other (Bhatt & Pai, 2009b; Liu et al., 2016) (Table 6). These two categories of study are described separately below.

Effects for training versus no training

With the exception of Bhatt et al. (2013) these studies all showed a point estimate indicating a benefit for perturbation training and the pooled effect was statistically significant [RR for laboratory-induced falling for perturbation training versus no training 0.17 (95% CI: 0.06 to 0.49)] (Figure 4). This effect could also be considered to be clinically important.

Study or Subgroup	Perturbation Events	Perturbation Total	Control Events	Control Total	Weight	Risk Ratio M-H, Fixed, 95% CI
Bhatt 2009b	0	8	3	8	16.9%	0.14 [0.01, 2.39]
Bhatt 2013	0	16	0	16		Not estimable
Lee 2016	1	24	3	12	19.3%	0.17 [0.02, 1.44]
Wang 2011	0	20	6	23	29.3%	0.09 [0.01, 1.47]
Yang 2013	0	17	4	17	21.7%	0.11 [0.01, 1.92]
Yang 2014	2	24	2	12	12.9%	0.50 [0.08, 3.13]
Total (95% CI)		**109**		**88**	**100.0%**	**0.17 [0.06, 0.49]**
Total events	3		18			

Heterogeneity: Chi² = 1.64, df = 4 (P = 0.80); I² = 0%
Test for overall effect: Z = 3.28 (P = 0.001)

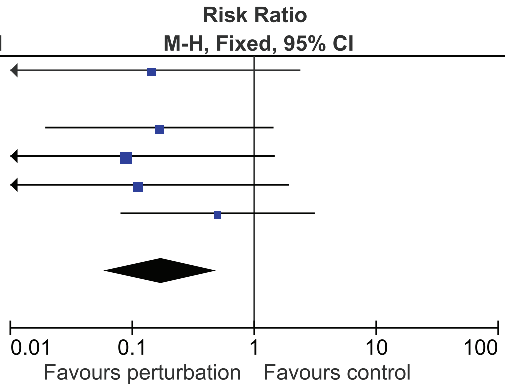

Figure 4: Forest plot for the effects of perturbation training compared to no perturbation training on risk of laboratory falls in young participants. For the trials where two perturbation lengths were tested, the 12 and 18 cm perturbation length results have been summated.

The pooled effect included summation of intervention falls rates in each of the two studies (Lee at al., 2016; Yang et al., 2014) where two perturbation lengths of 12cm and 18cm were tested against no treatment. Perturbation length did not appear to have a clear effect on falls rates, with the 12cm and 18cm perturbation length intervention groups each having 1/12 falls in the Yang et al. (2014) study, while the Lee et al. (2016) study demonstrated 1/12 falls in the 12cm group and 0/12 falls in the 18cm group.

It is important to note that in the Wang et al. (2011) study, two non-responders (defined by an inability to show any adaptive response during the training slips) in the intervention group were excluded from their analysis, thus increasing the risk of attrition bias. We performed a sensitivity analysis re-including these two participants, and their imputed values are based on the assumption that these would have fallen on the walking slip test. This imputation gave a more conservative pooled effect than otherwise [RR: 0.25 (95% CIs: 0.1 to 0.6)] but did not make an appreciable difference.

The lack of any effect in the Bhatt et al. (2013) study may be partially explained by its use of a simulated trip via the use of a physical obstacle, rather than a trip or slip induced by a treadmill or moving plates. Special glasses were used to prevent participants seeing the obstacle.

Yang et al. (2013) also considered another hypothesis – the effects of treadmill perturbation training versus overground perturbation training. The control group were subsequently given 24 induced slips on an over-ground walkway with moveable plates, and no falls were seen in either the treadmill or overground perturbation groups on a final over-ground slip test, initially suggesting treatment effects were similar. However there was a large difference in baseline falls (treadmill: 8/17; walkway: 4/17) indicating that the improvement might have been better for the treadmill training group.

Effects for intensity and frequency of training

In the study by Bhatt et al. (2009a) there was a significant difference between groups in incidence of backward balance loss at 4 months (p=0.04) with the greatest difference seen between the high intensity/high frequency group (lowest incidence of balance loss) and the low intensity/low frequency group (highest incidence of balance loss). In the Liu et al. (2016) study, 1/9 fell in the low intensity group, but none fell in the other three groups. These results weakly support the hypothesis that more intense training may be more beneficial in reducing falls.

Quality

Results for both the meta-analysis and the narrative analysis were graded as low quality (Tables 5 - 7). This was due to very serious risk of bias, largely due to selection and performance bias in most included studies.

Table 5: Characteristics of studies for review question 3 that compared perturbation training to no treatment. All participants were protected by a harness

Study name and type	Sample characteristics	Intervention	Comparator	Outcome measure	Risk of bias	Indirectness
Bhatt & Pai, 2009b RCT	16 young healthy subjects aged 26 years.	Repeated-slip training on a moveable platform set in a 7m walkway. 37 walking trials, including 24 trials where a slip was induced by the moveable plates. The participants were unaware of when slips would occur. All slips were on the right side.	No treatment	The ability to retain balance was tested on an oily floor surface. This occurred immediately after training. A single trial was used. Falls were defined as average force on the safety harness exceeding 4.5% body weight over any 1 second period after the slip onset.	Very serious. No allocation concealment. No assessor blinding.	None.
Bhatt et al., 2013 RCT	32 adults (26 women), aged 26 years.	Slip training including 8 slip perturbations simulated by a moveable platform set in a 7m walkway.	No treatment	An in-harness fall during a single trip induced during walking via a physical obstacle (the participants did not know when it would occur). This occurred immediately after training.	Very serious. No allocation concealment. No assessor blinding.	None.
Yang et al., 2013 Non-randomised	34 adults (16 female), aged 25.8 years.	15-20 forward slip-like perturbations during treadmill walking. The intensity of perturbations was adjusted to performance.	No treatment	As above	Very serious. Non random allocation with large baseline group discrepancies. No assessor blinding.	None.
Yang et al., 2014 Non-randomised	24 adults aged 24.9 years. 23/36 female.	Two intervention groups given perturbation training. 7 perturbations were applied using a 7m walkway with 2 moveable platforms over 18 trials. One group had 12cm slip perturbations while the other had 18cm slip perturbations.	No treatment	Balance loss was tested using an overground walking test where a 150 cm slip was given by moveable plates on a 7m walkway at a random trial. This occurred immediately after training.	Very serious. Non random allocation with large baseline group discrepancies. No assessor blinding.	None.

Study name and type	Sample characteristics	Intervention	Comparator	Outcome measure	Risk of bias	Indirectness
Lee et al., 2016 Non randomised	24 young adults aged 26.7 years, 18/24 female.	Two groups given perturbation training on treadmill. 7 forward slip-like perturbations applied during treadmill walking over 12 trials. One group had perturbations giving a slip distance of 12cm whilst the other had perturbations giving a slip distance of 18cm.	No treatment	As above	Very serious. Non random allocation with large baseline group discrepancies. No assessor blinding.	None.
Wang et al., 2011 Non randomised	43 young adults (26 women), aged 26 years.	With the participant sitting in a custom built chair a perturbation was applied on moving from sit to stand, by a pair of moveable plates. Participants performed 28 sit-stands, containing 14 slip perturbations.	No treatment	A fall (defined as >30% body weight detected by harness load cell) during a novel slip during walking on the walkway with two moveable plates was the outcome.	Very serious. Non-random allocation with large baseline group discrepancies. No assessor blinding.	None.

Table 6: Characteristics of studies for review question 3 that compared different intensities/frequencies of perturbation training. All participants were protected by a harness

Study name and type	Sample characteristics	Interventions to be compared	Outcome measure	Risk of bias	Indirectness
Bhatt & Pai, 2009a RCT	49 healthy young subjects (26 years).	Four groups experienced varying parameters of perturbations induced by moveable plates on a walkway. Slips were provided by moveable plates set in a 7m walkway, and participants were unaware of when a slip would occur. • High intensity, high frequency perturbation training - 24 slips on an initial session and 3 ancillary single slip training sessions. • High intensity, low frequency perturbation training - 24 slips on an initial session as above, but with no ancillary single slip training sessions. • Low intensity, high frequency perturbation training - a single slip on an initial session and 3 ancillary single slip training sessions. • Low intensity, low frequency perturbation training - a single slip on an initial session as above, but with no ancillary single slip training sessions.	Four months after the initial session participants were tested with a single slip test on the walkway. Falls were defined by 'backward balance loss' (where the contralateral leg lands behind the slipping heel).	Very serious. No allocation concealment. No assessor blinding.	None.
Liu et al., 2016 RCT	36 healthy young people of mean age 24.8 years	Four groups experienced varying parameters of perturbations induced by a treadmill. • High intensity group where 24 slips were experienced at an acceleration of 12 ms^{-2} • Low intensity group where 24 slips were experienced at an acceleration of 6 ms^{-2} • Increasing intensity group where perturbation accelerations increased from 6 ms-2 to 12 ms^{-2} over 18 perturbations and then from 6 ms^{-2} to 12 ms^{-2} over the final 6 perturbations. • Decreasing intensity group where perturbation accelerations decreased from 12 ms^{-2} to 6 ms^{-2} over 18 perturbations and then from 12 ms^{-2} to 6 ms^{-2} over the final 6 permutations.	In the same session, all subjects then walked down a 7m walkway and were given a single slip perturbation provided by moving plates. The definition of a fall was not provided.	Very serious. No allocation concealment. No assessor blinding.	None.

Table 7: Grade table summarising the quality of evidence for all questions

Number of studies (number of participants)	Risk of bias	Indirectness	Imprecision	Inconsistency	Outcome reporting bias	Publication bias	Grade
Community falls for perturbation combined with standard training vs standard training in older people							
1 (64)	Very serious[1]	Serious[2]	Very serious[3]	No serious inconsistency	None suspected	Unable to detect as <10 studies	Very low
Community falls for perturbation training vs non-standard training in older people							
4 (420)	Very serious[4]	Very serious[5]	Very serious[3]	No serious inconsistency	None suspected	Unable to detect as <10 studies	Very low
Laboratory falls for perturbation training vs no training in older people							
2 (97)	Very serious[6]	Very serious[7]	No serious imprecision	No serious inconsistency	None suspected	Unable to detect as <10 studies	Very low
Laboratory falls for perturbation training vs no training in older people (not meta-analysed)							
1 (48)	Very serious[8]	Very serious[9]	Very serious[10]	No serious inconsistency	None suspected	Unable to detect as <10 studies	Very low
Laboratory falls for perturbation training vs no training in younger people							
6 (199)	Very serious[11]	No serious indirectness	No serious imprecision	No serious inconsistency	None suspected	Unable to detect as <10 studies	Low
Laboratory falls for perturbation training vs no training in younger people - intensity and frequency effects (not meta-analysed)							
2 (85)	Very serious[12]	No serious indirectness	No serious imprecision	No serious inconsistency	None suspected	Unable to detect as <10 studies	Low

1 In the Lurie et al. (2013) study, there was no assessor blinding as well as likely attrition bias due to the exclusion from follow up and analysis of 5 subjects in the intervention group who did not attend for treatment.

2 Less than 50% participants were fallers at baseline in Lurie et al. (2013). The authors stated that participants were referred because they were at risk of falling but the criteria are unclear.

3 95% CIs crossed both 0.75 and 1.25 thresholds

4 Rosenblatt et al. (2013) used a pseudo-random alternate allocation approach, whilst none of the other randomised studies except Mansfield et al. (2010) used allocation concealment or had assessor blinding, and most had some degree of attrition bias and performance bias.

5 No studies used standard physiotherapy approaches as the comparator. Only Mansfield et al. (2010) had clear documentation that >50% of participants were fallers, and data concerning the extent to which participants in the other studies were deemed at risk of falling was unclear.

6 No reporting of allocation concealment in the Parijat and Lockhart (2012) study and a pseudo-randomisation procedure in the Grabiner et al. (2012) study. In addition, neither study ensured assessor blinding. Attrition bias likely in Grabiner et al. (2012)

7 The outcome also had very serious indirectness as the mean age was <65 (but >55) in the Grabiner et al. (2012) study, the comparators were non-standard treatment for both Parijat et al. (2012) and Grabiner et al. (2012), and there was no documentation in either study that the participants were fallers or at risk of falling.

8 No reporting of allocation concealment or assessor blinding, and potential attrition bias.

9 Comparator was no treatment and there was no documentation that the participants were fallers or at risk of falling.

10 p=0.5 in study

11 In the two randomised studies (Bhatt and Pai 2009b, 2013) neither reported allocation concealment, whilst in the non-randomised studies (Yang et al. 2013; Yang et al. 2014; Lee et al., 2016; Wang et al., 2011) the method of allocation was unclear. Furthermore, assessor blinding was not reported in any study. In Wang at al. (2011) two people in the perturbation group were excluded from analysis when it was likely they would have fallen had they not been excluded.

12 No reports of allocation concealment or assessor blinding in either study. In the Bhatt et al. (2009a) study attrition rates differed between groups, but this is unlikely to have related to outcome (these being a healthy sample) so attrition bias risk was probably low.

DISCUSSION

Our two meta-analyses relating to laboratory-induced falls in older and younger people clearly demonstrate that perturbation training has fall-prevention benefits compared to no treatment. The strong effect of perturbation training on falls in a laboratory setting appears to be similar between young and old, with both age groups demonstrating an approximately 6-fold decrease in laboratory falls frequency after perturbation training compared to no training. This is a qualitative impression as no direct age comparisons were conducted, but does agree with a study showing that older participants respond just as well to perturbation training as younger people (Pavol et al., 2002). This suggests that the mechanisms through which perturbation training exerts its benefits are not significantly attenuated by age. In particular the shift in reliance generated by perturbation training from reactive strategies towards a combination of feedforward and reactive strategies may be of particular advantage to older people. This is because feedforward strategies may be less affected by ageing effects on muscle power than the rapid 'emergency' movements involved in feedback responses.

In contrast, our other meta-analysis concerning the effects of perturbation training on community falls in older people suggests a more modest efficacy, with point-estimates of risk reductions of around 30% compared to the comparison treatment. Importantly there is considerable uncertainty about the true effect, indicating the possibility that no benefits may exist at all. The modest effect might relate to training specificity: it is intuitive that perturbation training conducted using laboratory equipment is more likely to promote recovery from falls induced on the same equipment than recovery from falls induced in the community. However some evidence (Bhatt & Pai, 2009a; Grabiner et al., 2012; Wang et al., 2011) suggests that the effects of perturbation training are generalisable to different contexts, and thus specificity may not necessarily be of prime importance. The relatively lower efficacy of perturbation training in the community falls studies might also relate to the fact that participants were generally older and frailer than those in the laboratory studies. For such participants, the low strength and power associated with frailty may be the limiting factor governing the ability to recover from a perturbation, rather than feedforward or reflexive stability control components, which are more amenable to perturbation training. However our inconclusive pooled results do not necessarily indicate that perturbation training is ineffective in preventing community falls. The quality of the meta-analysis for community falls was limited by the methodology and size of included studies, as well as the low number of eligible studies, which prevents a less ambiguous interpretation of findings. Further high quality trials may permit future meta-analyses to provide more certain results.

Only one study (Lurie et al., 2013) has evaluated the effects of perturbation training (combined with standard approaches) on community falls in older people, using standard best-practice falls prevention strategies as the comparator. Use of such a gold standard comparator is essential before it can be suggested that a combined perturbation training strategy is a new best-practice approach. The evidence from that single study was limited by the study not being adequately powered, and also by serious risks of attrition bias and detection bias. However, it weakly suggested that a combined perturbation approach might have some benefits over established methods. This reinforces the need for further work.

If perturbation training does have clinical efficacy, then one of the particular benefits of perturbation training may be its relatively rapid action (Pai et al., 2010b; Pai & Bhatt, 2007). Although limited evidence in younger people (Bhatt & Pai, 2009a; Liu et al., 2016) shows that more intense and frequent training may lead to even greater beneficial effects, the effects from just one session alone seem to be clinically important (Bhatt & Pai, 2009b; Bhatt et al., 2013; Grabiner et al., 2012; Lee et al., 2016; Pai et al., 2014a; Parijat et al. 2012; Wang et al., 2011; Yang et al., 2013; Yang et al., 2014). This rapid effect may be possible because this training may exert effects via immediate changes in CNS representation of the stable limits of the position of the centre of mass (Pai & Bhatt, 2007). It has also been suggested (Pai et al., 2014a) that the speed of such learning may be augmented by the fear induced by a training-induced (though harness-protected) fall, in accordance with animal studies showing that fear accelerates the development of adaptive synaptic pathways (Sacchetti, Scelfo, Tempia & Strata, 2004). In contrast, established approaches, which rely partially on the development of strength and power, may require several weeks of training for the neuromuscular adaptations to occur, and there are consequently likely to be greater problems with patient compliance and higher costs. Even if perturbation training is combined with standard approaches, as it probably should be given that the causes of falls are multifactorial, then the rapid benefits may still be beneficial. This is because any improvements in the proactive and reflexive aspects of postural stability may confer enough overall improvement (and perhaps confidence) to motivate continued standard training.

Another claim of the literature has been that the benefits of a single session of perturbation training may be relatively long-lived. Pai & Bhatt (2007) have discussed how updating of the stable limits of the COG, as part of a feedforward mechanism, may involve cortical and sub-cortical influences which might therefore be associated with longer-term memories. Accordingly, Bhatt et al. (2012) showed that both a single session of training and a single session combined with an ancillary session 3 months later led to continued gains at 6 months in younger people. Pai et al. (2014b) have also shown benefits lasting for up to 12 months in older people. However these results (which are not included in the main body of this systematic review) could be spurious as they were uncontrolled within-group gains, and thus prone to influence by intervening effects. No study has evaluated long-term outcomes using a control group and so it is still unclear if a single session is effective in leading to sustained benefits.

This systematic review has included data from younger people on the grounds that such studies are more likely to experiment with the parameters of training. However, there is currently insufficient evidence to allow definitive guidelines on the optimal parameters. The limited evidence suggests that slip perturbations of 12 cm length are probably sufficient (Lee et al., 2016; Yang et al., 2014), and that more frequent and/or intense sessions may be more effective (Bhatt et al., 2009; Liu et al., 2016). In addition, treadmill-induced perturbations may be slightly more effective than perturbations induced by shifting plates on a walkway (Yang et al., 2013), as well as being more practical, but this is far from clear.

Most of the evidence concerns training in the form of predominantly slip-type perturbations. However, it is known that real-world perturbations can be both slips and trips. So far only two studies (Grabiner et al., 2012; Rosenblatt et al., 2013) have estimated the effects of trip-like perturbation training on falls in older people. It is unknown if slip or trip training is superior and although the laboratory falls evidence in this review suggests each may have similar benefits (Grabiner et al., 2012; Parijat et al., 2012), this evidence is only in terms of how trip training protects against trip-induced falls and how slip-training protects against slip-induced falls. What remains to be seen is how well trip training relates to resistance to slips, and vice versa. Bhatt et al. (2013) attempted to establish the effects of slip training on resistance to trip-induced falls, but no falls were recorded in either intervention or control groups, making conclusions difficult.

It has been theorised that combining slip and trip training may actually be counter-productive because slip and trip training involve opposite stimuli – slip training promoting backward corrections due to the posterior rotation induced by the anterior slip perturbation, and trip training promoting forward corrections due to the anterior rotation induced by the posterior trip perturbation (Bhatt et al., 2013). However, in an extension to their comparative study, Bhatt et al. (2013) also showed that mixing approaches in the perturbation group did not adversely affect measures of stability. The authors concluded that the CNS was able to develop a generalised and adaptable movement strategy. This concurs with other findings. For example, in the Bhatt & Pai (2009b) study the slip perturbations trained on the treadmill transferred to reduced fall rates on a slippery floor. In the Wang et al. (2011) work, perturbations given during a sit-to-stand task transferred to greater falls resistance during walking. Similarly, in the study by Grabiner et al. (2012) perturbations provoked in standing appeared to carry over to protection of falls occurring during walking. Hence it is likely that trip training may carry over to protection from slips and vice versa. This generalisability is important as falls may occur in many different contexts, and perturbation training cannot hope to mimic all of them.

There are two main threats to a review capturing all the available data: 1) actual studies not being found by the search, and 2) failure of researchers to report relevant results or publish their data at all. In terms of the first threat, this systematic review used three databases, alongside cross-referencing, which make us confident that we have surveyed all the relevant literature. In terms of the second threat, we have no evidence to suggest there was any outcome-reporting bias or publication bias, although the latter was not possible to evaluate rigorously due to a small number of studies. One strength of this study was the use of two researchers to sift, extract and appraise all data. For the initial three sifts (Kappa scores: 0.83, 0.67 and 0.57 respectively) any papers selected by either author were automatically sought for further examination for maximum sensitivity. For the final selection of included papers and decisions on GRADE ratings, consensus was used where initial disagreement occurred (Kappa 0.78 and 0.57 respectively), and all were resolved to the satisfaction of both reviewers.

Ultimately, perturbation training is unlikely to be the 'magic bullet'. Even if reflex responses to perturbations are optimised these may not prevent falling in response to trips or slips if failing sensory systems or reduced muscle strength and power are the limiting factor. Furthermore, it has been estimated that 40% of falls are not related to slips or trips (Luukinen et al., 2000), so perturbation training may have limited effects on these. The ideal approach is therefore likely to involve a variety of approaches, based on detailed patient assessment.

CONCLUSION

The evidence that perturbation training has benefits over conventional approaches is unclear. Laboratory studies provide some evidence that perturbation training may have a place in falls prevention and further research is needed to confirm this. Perturbation training may exert effects after one session, but greater frequency and intensity of training may further increase effects.

KEY POINTS

1. Perturbation training is effective in reducing *laboratory-induced* falls in healthy young and older people,
2. Perturbation training may have rapid effects on reducing *laboratory-induced* falls, but the duration of effect is unclear.
3. Despite this, the efficacy of perturbation training in reducing *community falls* in healthy older people is uncertain, and further adequately powered and rigorous research is required before resources should be uncritically devoted to such an approach.

DISCLOSURES

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This article is lovingly dedicated to the memory of Valerie Perry (January 1928 - October 2016)

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