Book Chapter

Which Exercise Interventions Can Most Effectively Improve Reactive Balance in Older Adults? A Systematic Review and Network Meta-Analysis

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Abstract

Background: Reactive balance is the last line of defense to prevent a fall when the body loses stability, and beneficial effects of various exercise-based interventions on reactive balance in older adults have been reported. However, their pooled evidence on the relative effects has yet to be described.

Objective: To review and evaluate the comparative effectiveness of various exercise-based interventions on reactive balance in older adults

Methods: Nine electronic databases and reference lists were searched from inception to August 2021. Eligibility criteria according to PICOS criteria were as follows: (1) population: older adults with the mean age of 65 years or above; (2) intervention and comparison: at least two distinct exercise interventions or one exercise intervention with a no-exercise controlled intervention (NE) compared in each trial; (3) outcome: at least one measure of reactive balance; (4) study: randomized controlled trial. The main network meta-analysis was performed on data from the entire older adult population, involving all clinical conditions as well as healthy older adults. Subgroup analyses stratified by characteristics of participants (healthy only) and reactive balance outcomes (simulated slip or trip while walking, simulated forward falls, being pushed or pulled, and movable platform) were also conducted.

Results: Thirty-nine RCTs (n=1388) investigating 17 different types of exercise interventions were included in the network meta-analysis. Reactive balance training as a single intervention presented the highest probability (surface under the cumulative ranking (SUCRA) score) of being the best intervention for improving reactive balance and the greatest relative effects versus NE in the entire sample involving all clinical conditions (SUCRA=0.9; mean difference (95% Credible Interval): 2.7 (1.0 to 4.3)). The results were not affected by characteristics of participants (i.e., healthy older adults only) or reactive balance outcomes.

Summary/Conclusion: The findings from the NMA suggest that a task-specific reactive balance exercise could be the optimal intervention for improving reactive balance in older adults, and power training can be considered as a secondary training exercise.

Keywords

Older Adults; Aging; Balance; Reactive Balance; Exercise; Falls; Accidental Falls; Fall Prevention

Introduction

The World Health Organization reported that approximately 28-35% of people aged 65 or above experience at least one fall each year, and the frequency of falls increases with age and frailty level [1]. Among various intrinsic risk factors for falls, gait and balance problems have been considered the strongest risk factors [2,3]. Balance can be mechanistically achieved and maintained by a complex set of sensorimotor control systems including the multisensory (visual, somatosensory, and vestibular system) integration into the central nervous system and the subsequent motor output of the musculoskeletal system [4]. However, older adults show age-related decline in sensorimotor systems, which in turn increases the risks of falls [5,6]. Given the inherent and inevitable age-related degeneration in sensorimotor systems, it is becoming increasingly clear that in order to prevent potential repercussions, such as aging-related disease, disabilities, injuries, and falls, there is an urgent need for effective interventions to decelerate or even reverse the retrogression in the balance and gait control systems [7,8].

In daily life, reactive balance, referred to as the ability to control balance in response to mechanical disturbances, plays a critical role in avoiding and adapting to the complex environments that menace postural stability. The WHO Global Report on Falls Prevention in Older Age reported that factors related to the physical environment, for instance, uneven sidewalks, unmarked obstacles, and slippery surfaces, are some of the most common causes (30-50%) of falls in older adults [1]. Notably, slips and trips were the most prevalent causes of falls in regards to circumstances in older adults [9]. Reactive balance strategies, such as swaying around the ankle or hip joints, taking a reactive step, or reaching to grasp a handhold [4], need to be executed promptly so as to avoid falls following a postural perturbation. In the same vein, the balance recovery reactions have also shown age-related differences in older adults versus young adults and in fallers versus non-fallers [10,11].

There is a considerable amount of literature on the effects of a variety of interventions on reactive balance, including several systematic reviews and meta-analyses focusing on older adults [12-15]. However, there remain some limitations in the prior syntheses. First, the exercise interventions were limited to only those interventions focused on balance or strength training despite the existence of many studies that use exercises that specifically train reactive balance. Consequently, to the best of our knowledge, none of the previous reviews or meta-analyses have considered comparative effects between different types of exercises and the efficacy of multifaceted exercise interventions with more than one type of exercise on reactive balance. Thus, there is a need for a more comprehensive and inclusive analysis utilizing precise coding of exercise types targeting specific biological systems and functional aspects for better prescriptive guidance [8]. Second, the systematic review by Moore et al. [15] who examined the effectiveness of active physical training interventions on reactive balance did not perform a quantitative synthesis [15]. Consequently, there remains a lack of pooled evidence on the relative effects of different exercise interventions on reactive balance. Moreover, a conventional pairwise meta-analysis is restricted to a head-to-head comparison of only two different interventions, and thus, RCTs with other types of exercise interventions, that are also effective, can potentially be excluded. To tackle this problem, a network meta-analysis (NMA) is well suited, because it facilitates comparisons of multiple pairs of interventions in one statistical model [16].

Therefore, the current study aimed to quantitatively synthesize the available evidence of RCTs in detail using a systematic review and NMA to: (1) combine information from all available randomized comparisons of a set of exercise interventions for reactive balance in older adults; (2) to appraise the relative effects of different exercise interventions on reactive balance; and (3) to determine the ranking of each to provide practical and clinical suggestions to design evidence-based exercise programs for reactive balance. The research question was as follows:

"What type of exercise intervention is most effective in improving overall measures as well as each measure of reactive balance in older adults?"

Methods

The protocol was prospectively registered in the PROSPERO database (CRD42021256638) and conducted in accordance with the PRISMA extension statement for network meta-analysis [17].

Eligibility Criteria

The population of interest included older adults with a sample mean age of 65 years or above with no restriction on the injury or disorder type and with no history of falls studied in various research settings (e.g., community, clinics, and long-term care facilities). Studies were included, if at least two experimental groups participated in each of the different exercise interventions or if there was at least one exercise intervention group with a no-exercise control group. Studies involving any non-exercise interventions (e.g., medication, electrical stimulation, or nutritional supplement) were excluded. Details regarding the exercise interventions must have been provided in the reports. The studies must have included at least one reactive balance assessment, which is defined in this study as an assessment using mechanical postural perturbation during a static or dynamic steady-state task. The studies included in this review were restricted to randomized controlled trials (RCTs) and written in the English language.

Search Strategy

The following electronic databases were initially searched by one reviewer (Y.K.) from the inception to February 2021: MEDLINE, EBSCO, CINAHL, SPORTDiscus, PsycINFO, PubMed. WorldCat.org, OpenGrey.eu, and PROQUEST were additionally searched for unpublished trials. To keep this search up to date, an updated search followed in August 2021 by two reviewers (Y.K. and M.V.). Earlier reviews and bibliographies of included studies were reviewed for additional potentially relevant trials. The combination of the following keywords was employed for the database searches: (aged OR aging OR old* OR elder* OR senior*) AND (exercise OR train* OR activit* OR rehabilitat* OR therap* OR physiotherapy OR hydrotherapy OR conditioning OR exertion OR recreation* OR aerobic* OR stretch* OR strengthen* OR walk* OR jog* OR run* OR cycl* OR pilates OR yoga OR tai chi OR ai chi OR dance OR swim*) AND (reactive postural response OR stepping response OR perturbation OR slip perturbation OR reactive balance OR reactive stepping OR protective stepping OR compensatory stepping OR anticipatory postural adjustment* OR compensatory postural adjustment* OR anticipatory postural response* OR compensatory postural response* OR anticipatory adjustment* OR compensatory adjustment* OR postural adaptation* OR postural stabili*ation OR automatic postural response* OR postural stepping response*) AND (random*)

Study Selection

After exporting the references and removing duplicates, titles and abstracts of records were screened independently by two reviewers (Y.K. and M.V.) according to the eligibility criteria. Full texts of all potentially relevant trials were subsequently retrieved and reviewed to confirm the final eligible trials. Any disagreements were resolved via consensus, and when any disagreement was elusive, a third reviewer (E.B.) acted as an arbiter.

Data Extraction and Coding

A total of 46 eligible studies were reviewed and coded in REDCap (https://www.projectredcap.org/) by one reviewer (Y.K.) and confirmed by a second reviewer (M.V.). Any disagreements were resolved via consultation with a third reviewer (E.B.). The extracted data included: (1) study characteristics; (2) baseline demographics of participants; (3) exercise interventions; (4) reactive balance outcome measures; and (5) results. Exercise categorizations developed by Howe et al. and Sibley et al. were modified in consideration of the purpose of the current research and applied to the coding (Table 1) [8,18].

Table 1: Definitions of exercise types.

Exercise type	Code	Definitions
Single balance exercise including reactive balance component	SBR	An intervention including a balance exercise with one or more mechanical postural perturbations given during the exercise
Single balance exercise not including reactive balance component	SBNR	An intervention including a balance exercise without any mechanical postural perturbations
Multiple balance exercises including reactive balance component	MBR	An intervention including more than one type of balance exercise with one or more mechanical postural perturbations given during one of the exercises
Multiple balance exercises not including reactive balance component	MBNR	An intervention including more than one type of balance exercise without any mechanical postural perturbations
Unspecified balance exercise	balUS	Balance exercise without any details given in the original article
Gait training including reactive balance component	gaitR	An intervention including gait training with one or more mechanical postural perturbations given during the exercise
Gait training not including reactive balance component	gaitNR	An intervention including gait training without any mechanical postural perturbations
Whole body vibration	WBV	Any activity performed on a machine with a vibrating platform
Strength	str	Exercise that uses the external resistance load (e.g., body weight, resistance bands, machines) to force skeletal muscles contract.
Power	pw	Exercise that applies the maximum amount of force (muscle contraction against a resistance) in the shortest period of time.

3D exercise	3d	Exercise that requires multi-dimensional movements with a specific name of the exercise (e.g., Yoga, dance, Tai Chi)
Flexibility	flex	Exercise that intends to restore or maintain the optimal range of motion (ROM) available to a joint or joints.
Functional training	FT	Exercise that utilizes functional activities as the training stimulus that is based on the theoretical concept of task specificity
Aerobic	aer	Exercise aimed at cardiovascular conditioning. It is aerobic in nature and simultaneously increases the heart rate and the return of blood to the heart.
No exercise	NE	A group received none of the exercise interventions listed above

Means (M) and standard deviations (SD) for all eligible outcomes of reactive balance measures at baseline and post-intervention were extracted for the analysis. Missing data related to eligibility and study outcomes (i.e., data not reported either in a text or on publicly accessible data repositories) were requested to the corresponding authors via email. In the case of no response after one month, a second request was sent, if another month elapsed without response, the data were considered irretrievable. If the requested, but not retrieved data were presented in a graphical format rather than numeric data (e.g., tabular format), Engauge Digitizer 12.1 (http://markummitchell.github.io/engauge-digitizer/) was applied for data digitization and extraction.

Risk of Bias

To ascertain an overall and study-level risk of bias for each trial, a pair of reviewers (Y.K. and M.V.) independently determined the bias arising from the following domains using the Cochrane risk of bias tool (RoB 2): (1) randomization process; (2) deviations from the intended interventions; (3) missing outcome data; (4) measurement of the outcome; and (5) selection of the reported result [19]. Each domain was assigned a judgement of "low risk," "some concerns," or "high risk." Disagreements were resolved through discussion or referral to a third reviewer (E.B.).

Data Synthesis and Statistical Analysis

Considering indeterminate baseline similarities of reactive balance measures in several studies, change values from baseline to post-intervention were calculated or directly extracted from the published data. If there were more than one post-intervention measure (e.g., post-intervention and follow-up), only the data immediately following the termination of the intervention phase was used. SDs for changes from baseline (pre) to post-intervention (post) were calculated using the following formula [20]:

$$SD_{change} = \sqrt{{SD_{pre}}^{2} + {SD_{post}}^{2} - 2 * Corr * SD_{pre} * SD_{post}}$$

Corr in the SD_{change} equation is the correlation coefficient describing how similar the pre and post-interventions were across participants. When the correlation coefficient was not reported, it was set as 0.5 [21-24]. In the case of a lower score signifying better performance in reactive balance measures (e.g., reaction time), scale directions were adjusted by multiplying -1 to the M_{change} data, which led to a greater effect size indicating an improvement. Missing SDs were imputed from standard errors (SE), 90%, or 95% confidence intervals (CI). Using the M_{change} and SD_{chang} data, standardized mean differences (SMD) and standard errors (SE) were calculated.

To include multi-arm trials, two approaches were adopted to avoid a unit-of-analysis error [20,25]. First, all relevant experimental intervention groups composed of the same categories of exercises were combined into a single group. This step enabled a single pairwise comparison between a combined group and a comparison group in each study. Second, in the case of heterogeneous exercise types across all intervention groups, we included all relevant comparisons as a series of two-arm comparisons and reflect the fact that comparisons within multi-arm studies are correlated [26]. Accordingly, adjusted SEs of the two-arm comparisons in each multi-arm study were computed using “netmeta” package in R software. The majority of the eligible trials consisted of multiple outcomes in each trial. When multiple SMDs were estimated in a single study, therefore, a pooled SMD with SE was computed.

To estimate the comparative effectiveness of exercise-based interventions on reactive balance, we implemented NMA, which incorporates both direct (i.e., head-to-head comparison from pairwise meta-analysis) and indirect comparisons (i.e., from network meta-analysis) in one statistical model. A Bayesian framework of NMA was conducted using Markov chain Monte Carlo simulations, and non-informative prior distributions for treatment effects were adopted [16,27]. A random-effects model was used considering the clinical and methodological between-study heterogeneity [28,29]. The NMA was conducted for all available exercise interventions included in at least two trials. The analyses utilized a burn-in period (50,000 iterations) and a follow-up period (100,000 iterations) to minimize bias of initial values when the chain reached its target distribution [30]. The convergence was assessed using the trace plot, density plot, and Brooks-Gelman-Rubin diagnostic statistics [30].

The overall geometry of the network was presented in a network graph. Based on Bayesian posterior rank probabilities, the ranking of exercise interventions was estimated using a hierarchical tool, the surface under the cumulative ranking curve (SUCRA) score, measured on a scale from 0 (theoretically the worst) to 1 (the best). In addition, a network forest plot was produced with the “no exercise (NE)” as a reference intervention. The posterior distribution of the SMDs was reported using the mean differences fto the reference intervention with 95% credible intervals (CrI), which indicate that there is a 95% probability that the unobserved (unknown) effect estimates would fall within the intervals [31]. If a 95% CrI contains zero (i.e., null effect representing the null hypothesis), the effect can be considered statistically insignificant [31]. The relative effects with 95% CrI of all pairs of exercise interventions were reported in a matrix. Consistency, which is the most important assumption underlying a NMA and indicates agreement between direct and indirect estimates in the network [32], was checked using the node-splitting analysis. The original intention of the first subgroup analysis was to conduct a network meta-analysis stratified by characteristics of participants (i.e., healthy and disease-specific). However, due to the insufficient number of exercise interventions to establish a network in each disease category (e.g., Parkinson's disease), the first subgroup analysis was performed by the inclusion of studies with healthy older adults only (78% of all studies) who did not have any disease, injury, or disability at the time of the studies. The second subgroup analysis was conducted by grouping the outcome measures by the types of reactive balance outcomes: (1) simulated slip or trip while walking; (2) simulated forward falls; (3) being pushed or pulled; (4) movable platform; and (5) balance test battery. A sensitivity analysis was carried out using a frequentist framework NMA to appraise the robustness of the results. Sources of statistical heterogeneity and small study bias were not explored due to the insufficient number of trials ($k \leq 5$) for each comparison. All data syntheses and statistical analyses were conducted using "Gemtc" (version 1.0-1), "rjags" (version 4-10), and "netmeta" (version 1.4-0) packages in R (Version 4.1.0, R Foundation for Statistical Computing, Vienna, Austria).

Results

Study Selection

A total of 7394 records were retrieved from electronic databases and two additional records were obtained from other sources, of which 384 studies remained after removing duplicates and screening titles and abstracts. Based on the full-text screening, 46 records fulfilled the eligibility criteria and thus were included for qualitative analysis (i.e., systematic review), whereas seven studies were additionally excluded from the quantitative analysis (i.e., network meta-analysis) due to data not being reported and not irretrievable [33-35], exercise types not included in the network [36,37], exercise intervention included in only one trial [38], and no continuous data reported [39], resulting in a total of 39 studies for NMA. The schematic flow chart for the selection process is presented in Figure 1, and all included studies are listed in Supplementary Table 1.

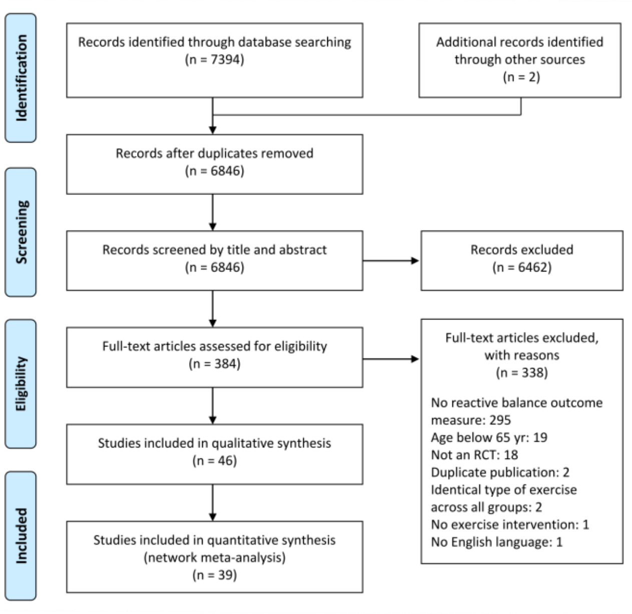


Figure 1: PRISMA flow diagram of study selection

Characteristics of Included Studies

The eligible studies represented a total of 1745 older adults, included in both pre and post-intervention analyses, with the mean age of 71.9 ± 3.9 years (ranged from 65.3-80.9 years). The majority of the studies exclusively included community-dwelling healthy older adults (k = 36). Ten studies reported on older adults selected for a specific disease or medical condition, such as Parkinson's disease (k = 6), post-surgical interventions for knees, hips, or backs (k = 2), postmenopausal women with osteopenia (k = 1), and chronic stroke (k = 1).

The duration and frequency of the exercise interventions ranged from 1 week to 1 year, 1-5 sessions/week, and 15-90 min/session. Of the 46 studies, 16 executed multicomponent (i.e., multifaceted) exercise interventions in at least one group. Reactive balance was assessed before and after the exercise interventions by use of laboratory-induced slip, trip, and falls, external impacts (e.g., pulling or pushing a body part), platform translation, and treadmill perturbation (e.g., rapid change of the speed) while participants were performing a steady-state task, such as standing or walking. Twenty studies provided training with a postural perturbation while standing or walking, and 11 of which implemented task-specific training (i.e., comparable reactive balance task included in the assessment and training) [34,35,38-47]. The characteristics of the participants and exercise interventions are presented in Tables 2 and 3, respectively. Outcome measures and main findings are summarized in Supplementary Tables 2.

Risk of Bias

The summary of the risk of bias assessment across all included studies is presented in Figure 2. Detailed results of the assessment are reported in Supplementary Table 3. Overall, the majority of outcomes were at some concerns (50%) and high risk (48%), and only one study was rated as at low risk. Missing outcome data (46%) was the most influential source of high risk of bias. Selection of the reported result (83%), randomization process (76%), and deviations from intended interventions (61%) were also common sources of bias.

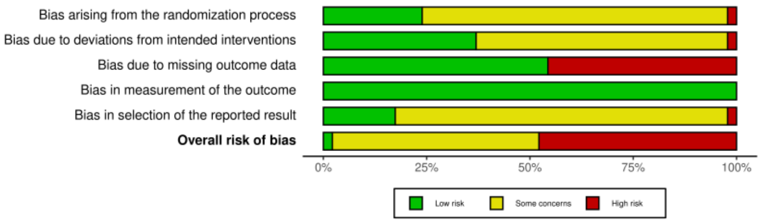


Figure 2: Summary of the distributions of the reviewers' judgements across the studies for each risk of bias domain.

Table 2: Characteristics of participants.

Study	Disease category	Sample size (post-intervention)	Attrition rate (%)	Age (years)
Allin 2020	Healthy	34 (29)	15	70.4
Arampatzis 2011	Healthy	55 (38)	31	67.7
Arghavani 2020	Healthy (fallers: 6 months)	60 (49)	18	69.6
Beling 2009	Healthy	23 (19)	17	80.0
Bieryla 2007	Healthy	12 (11)	8	73.3
Bogaerts 2007	Healthy	220 (161)	27	67.1
Cabrera-Martos 2020	Parkinson's	44 (44)	0	76.5
Cherup 2019	Parkinson's	42 (35)	17	71.2
Chyu 2010	Postmenopausal women with osteopenia	61 (53)	13	71.9
Donath 2016	Healthy	59 (48)	19	69.7
Gatts 2007	Healthy (balance deficiency without any neurological disorder); Arthritis, back, knee, or hip surgery not excluded.	22 (19)	14	77.6
Gatts 2008	Healthy (balance deficiency without any neurological disorder); Arthritis, back, knee, or hip surgery not excluded.	22 (19)	14	77.6
Granacher 2006	Healthy	60 (60)	0	66.5
Granacher 2009	Healthy	40 (40)	0	67.0
Hamed 2018	Healthy	63 (47)	25	71.2
Hatzitaki 2009	Healthy	56 (56)	0	70.9
Hu 1994	Healthy	24 (24)	0	75.2
Inacio 2018	Healthy	18 (18)	0	71.9
Jagdhane 2016	Healthy	6 (6)	0	73.3
Kim 2010	Healthy	18 (18)	0	NS
Klamroth 2019	Parkinson's	43 (37)	14	65.3
Lacroix 2016	Healthy	66 (60)	9	72.8
Li 2009	Healthy	50 (40)	20	65.3
Ma 2019	Healthy	33 (24)	27	69.8
Mansfield 2010	Healthy (fallers: 5 years)	34 (30)	12	69.7
Marigold 2005	chronic stroke	59 (48)	19	67.8
Morat 2019	Healthy	51 (45)	12	69.4
Ni 2014	Healthy	48 (39)	19	74.2
Ochi 2015	Healthy	20 (20)	0	80.6
Okubo 2019	Healthy	44 (41)	7	72.1
Pamukoff 2014	Healthy (some lower extremity mobility dysfunction)	20 (15)	25	70.8
Parijat 2012	Healthy	24 (24)	0	72.7
Parijat 2015a	Healthy	24 (24)	0	72.4

Parijat 2015b	Healthy	24 (24)	0	72.4
Pluchino 2012	Healthy	40 (27)	33	72.1
Qutubuddin 2007	Parkinson's	22 (15)	32	72.8
Rieger 2020	Healthy	30 (30)	0	71.0
Rossi 2014	Healthy	46 (46)	0	67.5
Santos 2017	Parkinson's	40 (40)	0	67.8
Schlenstedt 2015	Parkinson's	40 (32)	20	75.7
Shimada 2003	Healthy	34 (32)	6	80.9
Sohn 2015	Healthy	18 (18)	0	73.7
Thomas 2016	Healthy	24 (24)	0	67.1
Wang 2019	Healthy	146 (146)	0	72.7
Wolf 1997	Healthy	72 (54)	25	76.9
Wooten 2018	Healthy (fallers: 1 year)	30 (16)	47	72.6

Table 3: Summary of exercise interventions.

Study	Dosage		Total duration (week)	Exercise interventions		
	Min /session	Time /week		Group1	Group2	Group3
Allin 2020	30-60	2	2	SBR + gaitR	MBNR + gaitNR + str	
Arampatzis 2011	90	2	14	MBR	SBNR + str	NE
Arghavani 2020	60	3	8	SBR	MBNR + gaitNR + str	NE
Beling 2009	60	3	12	MBR + gaitNR + flex + str	NE	
Bieryla 2007	15	1	1	gaitR	gaitNR	
Bogaerts 2007	40-90	3	1 year	MBNR + WBV	SBNR + str + flex + aer	NE
Cabrera-Martos 2020	45	3	8	FT	FT + flex	
Cherup 2019	60	2	12	pw	Str	
Chyu 2010	60	3	24	3d	NE	
Donath 2016	66	2	8	3d	MBNR	NE
Gatts 2007	90	5	3	3d	SBNR + flex	
Gatts 2008	90	5	3	3d	SBNR + flex	
Granacher 2006	60	3	13	str	SBNR	NE
Granacher 2009	60	3	13	str	NE	
Hamed 2018	90	2	14	str	SBR	NE
Hatzitaki 2009	30	3	4	SBNR	SBNR	NE
Hu 1994	60	10 sessions (total)	15 days (total)	SBNR	NE	
Inacio 2018	15	3	8	pw	str	
Jagdhane 2016	60	3	4	SBR	NE	
Kim 2010	NR	NR	8	str	MBNR	NE
Klamroth 2019	40	2	8	gaitR	gaitNR	
Lacroix 2016	45	3	12	MBNR + str + pw	MBNR + str + pw	NE
Li 2009	60	4 for 6weeks, 7 for 10 weeks	16	3d	NE	
Ma 2019	60	2	12	3d	NE	
Mansfield 2010	30	3	6	SBR	SBNR + flex	

Marigold 2005	60	3	10	MBR + gaitNR	SBNR + flex	
Morat 2019	40	3	8	SBR	SBNR	NE
Ni 2014	60	2	12	3d	MBNR	3d
Ochi 2015	30	3	12	MBNR + WBV	SBNR + str	
Okubo 2019	40	3	1	gaitR	gaitNR	
Pamukoff 2014	60	3	6	pw	str	
Parijat 2012	40	1	1	gaitR	gaitNR	
Parijat 2015a	35-55	1	1	gaitR	gaitNR	
Parijat 2015b	35-55	1	1	gaitR	gaitNR	
Pluchino 2012	60	2	8	MBNR + gaitNR	3d	MBNR
Qutubuddin 2007	30	2	4	balUS	MBNR + gaitNR	
Rieger 2020	NS	1	1	gaitR	gaitNR	
Rossi 2014	40	3	6	SBNR	NE	
Santos 2017	60	2	8	str + flex	MBR + gaitNR	
Schlenstedt 2015	60	2	7	str	MBR	
Shimada 2003	40	2-3	12	MBNR	gaitNR	str + flex
Sohn 2015	60	3	8	str	balUS	NE
Thomas 2016	70	2	6	MBNR	NE	
Wang 2019	30	1	1	gaitR	gaitNR	
Wolf 1997	60	1-2	15	MBR	NE	3d
Wooten 2018	45	3	6	MBNR	3d	

SBR, Single balance exercise including reactive balance component; SBNR, Single balance exercise not including reactive balance component; MBR, Multiple balance exercises including reactive balance component; MBNR, Multiple balance exercises not including reactive balance component; balUS, Unspecified balance exercise; gaitR, Gait training including reactive balance component; gaitNR, Gait training not including reactive balance component; WBV, Whole body vibration; str, Strength; pw, Power; 3d, 3D exercise; FT, Functional training; flex, Flexibility; aer, Aerobic; NE, No exercise.

Network Meta-Analysis

Data from a total of 39 studies (n = 1388, age = 71.5 ± 3.9 years) were included in the NMA. Of the 15 exercise types reported in Table 1, 14 types were included in the NMA as functional training was implemented in only one study and consequently included in a disconnected network [37]. There were 11 multi-arm trials, and three of which consisted of two groups sharing the same exercise type and the third group with another type [38,48,49]; thus, data in these two groups were combined into a single group. Two exercise groups in studies by Gatts [50,51], str and NE groups in studies by Granacher et al. [52,53], and two exercise groups in studies by Parijat et al. [54,55] shared the same participants, respectively. Thus, each of the aforementioned pairs of studies was combined as a single study in NMA. Overall, 17 exercise interventions with either single or multiple exercise components were included in the NMA. The geometric distribution of the network is depicted in Figure 3. When a study involves a trial arm with a combination of the pre-categorized exercise types, the combination was considered as another distinct exercise intervention.

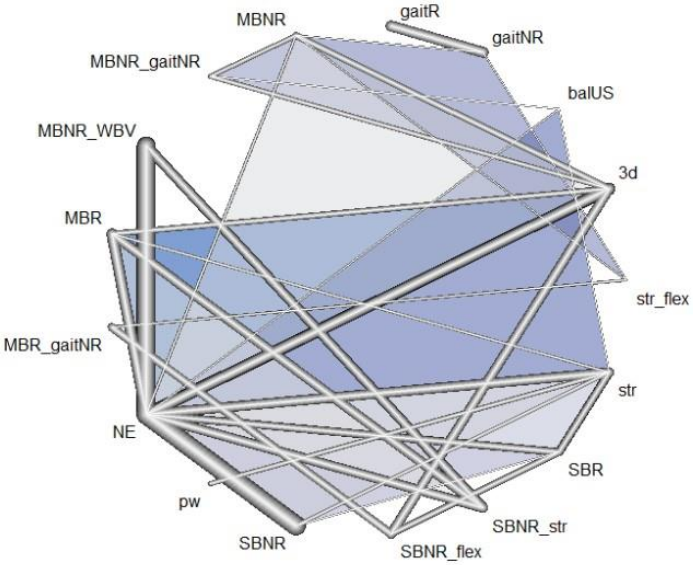


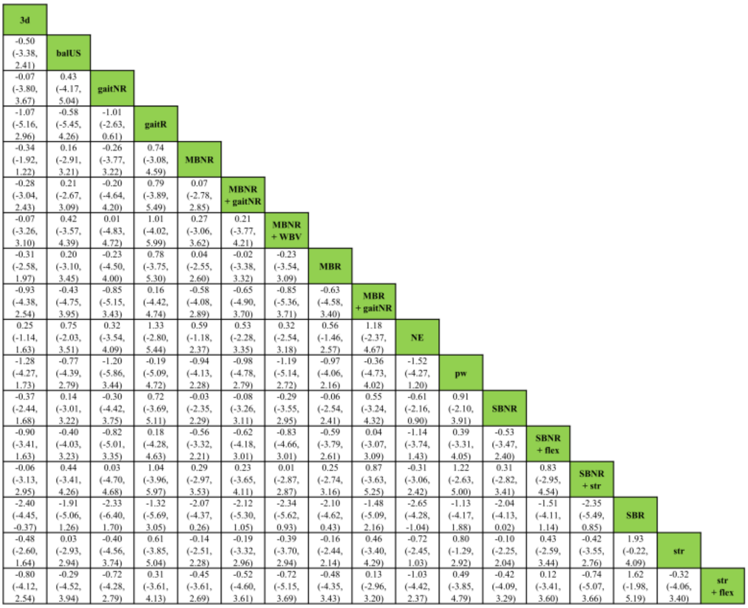
Figure 3: Network geometry of the included exercise programs: Each line indicates a direct comparison of two different exercise programs. The thickness of the edge is proportional to the number of direct comparisons in the network. Different exercise types combined in one program are connected via underscores. The blue triangles refer to multi-arm trials comprised of three exercise programs in the nodes. SBR, Single balance exercise including reactive balance component; SBNR, Single balance exercise not including reactive balance component; MBR, Multiple balance exercises including reactive balance component; MBNR, Multiple balance exercises not including reactive balance component; balUS, Unspecified balance exercise; gaitR, Gait training including reactive balance component; gaitNR, Gait training not including reactive balance component; WBV, Whole body vibration; str, Strength; pw, Power; 3d, 3D exercise; flex, Flexibility; aer, Aerobic; NE, No exercise.

Estimates of all exercise programs against all others in NMA were reported in a matrix (Figure 4). In the 17 exercise programs, SBR displayed the highest probability of being the most effective exercise intervention (SUCRA score=0.90) for improving reactive balance, followed by pw (SUCRA score=0.67) and gaitR (SUCRA score=0.62) (Table 4).

Table 4: Ranking of exercise interventions.

Bayesian framework			Frequentist framework		
Ranking	Exercise	SUCRA score	Ranking	Exercise	P-score
1	SBR	0.90	1	SBR	0.94
2	pw	0.67	2	pw	0.70
3	gaitR	0.62	3	gaitR	0.64
4	SBNR + flex	0.58	4	SBNR + flex	0.61
5	MBR + gaitNR	0.58	5	MBR + gaitNR	0.60
6	str + flex	0.55	6	str + flex	0.57
7	balUS	0.49	7	balUS	0.49
8	str	0.49	8	str	0.49
9	SBNR	0.46	9	SBNR	0.46
10	MBNR	0.46	10	MBNR	0.45
11	MBR	0.45	11	MBR	0.44
12	MBNR + gaitNR	0.44	12	MBNR + gaitNR	0.43
13	MBNR + WBV	0.40	13	MBNR + WBV	0.38
14	SBNR + str	0.40	14	SBNR + str	0.37
15	gaitNR	0.39	15	gaitNR	0.37
16	3d	0.35	16	3d	0.33
17	NE	0.27	17	NE	0.23

SBR, Single balance exercise including reactive balance component; SBNR, Single balance exercise not including reactive balance component; MBR, Multiple balance exercises including reactive balance component; MBNR, Multiple balance exercises not including reactive balance component; balUS, Unspecified balance exercise; gaitR, Gait training including reactive balance component; gaitNR, Gait training not including reactive balance component; WBV, Whole body vibration; str, Strength; pw, Power; 3d, 3D exercise; flex, Flexibility; aer, Aerobic; NE, No exercise.



3d																
-0.50 (-3.38, 2.41)	**balUS**															
-0.07 (-3.80, 3.67)	0.43 (-4.17, 5.04)	**gaitNR**														
-1.07 (-5.16, 2.96)	-0.58 (-5.45, 4.26)	-1.01 (-2.63, 0.61)	**gaitR**													
-0.34 (-1.92, 1.22)	0.16 (-2.91, 3.21)	-0.26 (-3.77, 3.22)	0.74 (-3.08, 4.59)	**MBNR**												
-0.28 (-3.04, 2.43)	0.21 (-2.67, 3.09)	-0.20 (-4.64, 4.20)	0.79 (-3.89, 5.49)	0.07 (-2.78, 2.85)	**MBNR + gaitNR**											
-0.07 (-3.26, 3.10)	0.42 (-3.57, 4.39)	0.01 (-4.83, 4.72)	1.01 (-4.02, 5.99)	0.27 (-3.06, 3.62)	0.21 (-3.77, 4.21)	**MBNR + WBV**										
-0.31 (-2.58, 1.97)	0.20 (-3.10, 3.45)	-0.23 (-4.50, 4.00)	0.78 (-3.75, 5.30)	0.04 (-2.55, 2.60)	-0.02 (-3.38, 3.32)	-0.23 (-3.54, 3.09)	**MBR**									
-0.93 (-4.38, 2.54)	-0.43 (-4.75, 3.95)	-0.85 (-5.15, 3.43)	0.16 (-4.42, 4.74)	-0.58 (-4.08, 2.89)	-0.65 (-4.90, 3.70)	-0.85 (-5.36, 3.71)	-0.63 (-4.58, 3.40)	**MBR + gaitNR**								
0.25 (-1.14, 1.63)	0.75 (-2.03, 3.51)	0.32 (-3.54, 4.09)	1.33 (-2.80, 5.44)	0.59 (-1.18, 2.37)	0.53 (-2.28, 3.35)	0.32 (-2.54, 3.18)	0.56 (-1.46, 2.57)	1.18 (-2.37, 4.67)	**NE**							
-1.28 (-4.27, 1.73)	-0.77 (-4.39, 2.79)	-1.20 (-5.86, 3.44)	-0.19 (-5.09, 4.72)	-0.94 (-4.13, 2.28)	-0.98 (-4.78, 2.79)	-1.19 (-5.14, 2.72)	-0.97 (-4.06, 2.16)	-0.36 (-4.73, 4.02)	-1.52 (-4.27, 1.20)	**pw**						
-0.37 (-2.44, 1.68)	0.14 (-3.01, 3.22)	-0.30 (-4.42, 3.75)	0.72 (-3.69, 5.11)	-0.03 (-2.35, 2.29)	-0.08 (-3.26, 3.11)	-0.29 (-3.55, 2.95)	-0.06 (-2.54, 2.41)	0.55 (-3.24, 4.32)	-0.61 (-2.16, 0.90)	0.91 (-2.10, 3.91)	**SBNR**					
-0.90 (-3.41, 1.63)	-0.40 (-4.03, 3.23)	-0.82 (-5.01, 3.35)	0.18 (-4.28, 4.63)	-0.56 (-3.32, 2.21)	-0.62 (-4.18, 3.01)	-0.83 (-4.66, 3.01)	-0.59 (-3.79, 2.61)	0.04 (-3.07, 3.09)	-1.14 (-3.74, 1.43)	0.39 (-3.31, 4.05)	-0.53 (-3.47, 2.40)	**SBNR + flex**				
-0.06 (-3.13, 2.95)	0.44 (-3.41, 4.26)	0.03 (-4.70, 4.68)	1.04 (-3.96, 5.97)	0.29 (-2.97, 3.53)	0.23 (-3.65, 4.11)	0.01 (-2.87, 2.87)	0.25 (-2.74, 3.16)	0.87 (-3.63, 5.25)	-0.31 (-3.06, 2.42)	1.22 (-2.63, 5.00)	0.31 (-2.82, 3.41)	0.83 (-2.95, 4.54)	**SBNR + str**			
-2.40 (-4.45, -0.37)	-1.91 (-5.06, 1.26)	-2.33 (-6.40, 1.70)	-1.32 (-5.69, 3.05)	-2.07 (-4.37, 0.26)	-2.12 (-5.30, 1.05)	-2.34 (-5.62, 0.93)	-2.10 (-4.62, 0.43)	-1.48 (-5.09, 2.16)	-2.65 (-4.28, -1.04)	-1.13 (-4.17, 1.88)	-2.04 (-4.13, 0.02)	-1.51 (-4.11, 1.14)	-2.35 (-5.49, 0.85)	**SBR**		
-0.48 (-2.60, 1.64)	0.03 (-2.93, 2.94)	-0.40 (-4.56, 3.74)	0.61 (-3.85, 5.04)	-0.14 (-2.51, 2.28)	-0.19 (-3.32, 2.96)	-0.39 (-3.70, 2.94)	-0.16 (-2.44, 2.14)	0.46 (-3.40, 4.29)	-0.72 (-2.45, 1.03)	0.80 (-1.29, 2.92)	-0.10 (-2.25, 2.04)	0.43 (-2.59, 3.44)	-0.42 (-3.55, 2.76)	1.93 (-0.22, 4.09)	**str**	
-0.80 (-4.12, 2.54)	-0.29 (-4.52, 3.94)	-0.72 (-4.28, 2.79)	0.31 (-3.61, 4.13)	-0.45 (-3.61, 2.69)	-0.52 (-4.60, 3.61)	-0.72 (-5.15, 3.69)	-0.48 (-4.35, 3.43)	0.13 (-2.96, 3.20)	-1.03 (-4.42, 2.37)	0.49 (-3.85, 4.79)	-0.42 (-4.09, 3.29)	0.12 (-3.41, 3.60)	-0.74 (-5.07, 3.66)	1.62 (-1.98, 5.19)	-0.32 (-4.06, 3.40)	**str + flex**

Figure 4: Relative effect estimates with 95% credible intervals of all pairs of exercise interventions

The relative treatment effect estimates of each exercise program with the no-exercise program being the mutual contrast for comparison are presented in a forest plot (Figure 5). SBR, pw, and gaitR demonstrated the largest mean difference versus NE; however SBR only demonstrated a statistically significant difference when compared to the no-exercise program (mean difference = 2.7, 95% CrI = 1.0 to 4.3). The trace plot, density plot, and Brooks-Gelman-Rubin diagnostic statistics showed good convergence, which signifies our data has converged to a reasonable distribution. Relatively reliable evidence was derived from the statistical consistency between direct and indirect evidence demonstrated by the node-splitting model ($p > 0.05$). According to the sensitivity analysis using a Frequentist framework of NMA, the ranking based on the P-scores showed identical results (Table 4). The results suggest that our main findings regarding the relative effectiveness of each exercise intervention are robust for future decisions.

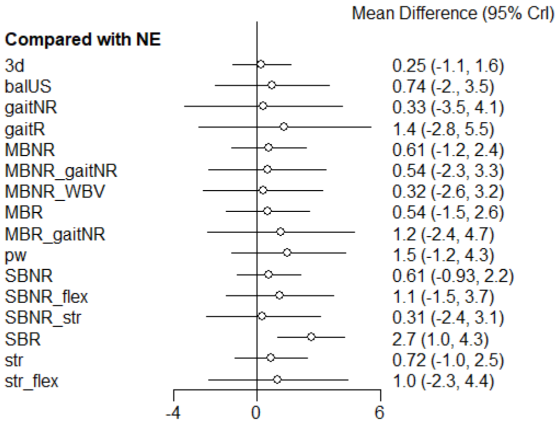


Figure 5: Forest plot of the relative effects of exercise interventions with a no-exercise as a reference group. SBR, Single balance exercise including reactive balance component; SBNR, Single balance exercise not including reactive balance component; MBR, Multiple balance exercises including reactive balance component; MBNR, Multiple balance exercises not including reactive balance component; balUS, Unspecified balance exercise; gaitR, Gait training including reactive balance component; gaitNR, Gait training not including reactive balance component; WBV, Whole body vibration; str, Strength; pw, Power; 3d, 3D exercise; flex, Flexibility; aer, Aerobic; NE, No exercise.

Subgroup Analyses

In the subgroup analysis for healthy older adults (k = 29, n = 1120, age = 71.5 ± 3.7 years), effects of 12 exercise programs were compared (Figure 6).

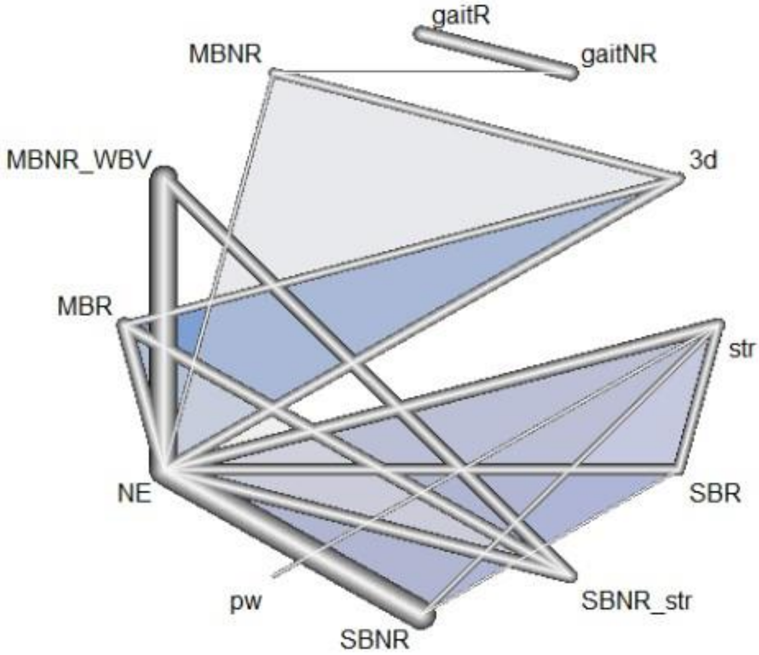


Figure 6: Network geometry of the included exercise programs in healthy older adults: Each line indicates a direct comparison of two different exercise programs. The thickness of the edge is proportional to the number of direct comparisons in the network. Different exercise types combined in one program are connected via underscores. The blue triangles refer to multi-arm trials comprised of three exercise programs in the nodes. SBR, Single balance exercise including reactive balance component; SBNR, Single balance exercise not including reactive balance component; MBR, Multiple balance exercises including reactive balance component; MBNR, Multiple balance exercises not including reactive balance component; gaitR, Gait training including reactive balance component; gaitNR, Gait training not including reactive balance component; WBV, Whole body vibration; str, Strength; pw, Power; 3d, 3D exercise; NE, No exercise.

According to the SUCRA scores, SBR was the highest-ranked exercise program (0.90), followed by pw (0.71), which was consistent with the ranking in the complete sample (Table 5). The other exercise programs ranked slightly differently from the NMA for the complete sample; however, the rankings based on the SUCRA scores were consistent with those estimated by P-scores in the frequentist framework (Table 5). The relative effects of all exercise interventions compared to NE were presented in Figure 7. A relative effect matrix was additionally created for all comparisons in the healthy older adults (Figure 8). Too few trials in other disease categories (Parkinson’s disease: 6 trials, arthritis: 2 trials, osteopenia: 1 trial) and types of exercise interventions were available to establish a network in each category and conduct further disease-specific subgroup analyses.

Table 5: Ranking of exercise interventions in healthy older adults.

Bayesian framework			Frequentist framework		
Ranking	Exercise	SUCRA score	Ranking	Exercise	P-score
1	SBR	0.90	1	SBR	0.95
2	pw	0.71	2	pw	0.76
3	str	0.52	3	str	0.53
4	gaitR	0.52	4	gaitR	0.52
5	SBNR	0.50	5	SBNR	0.52
6	MBR	0.47	6	MBR	0.47
7	MBNR	0.46	7	MBNR	0.46
8	MBNR + WBV	0.43	8	MBNR + WBV	0.41
9	SBNR + str	0.42	9	SBNR + str	0.41
10	gaitNR	0.40	10	gaitNR	0.37
11	3d	0.35	11	3d	0.32
12	NE	0.32	12	NE	0.28

SBR, Single balance exercise including reactive balance component; SBNR, Single balance exercise not including reactive balance component; MBR, Multiple balance exercises including reactive balance component; MBNR, Multiple balance exercises not including reactive balance component; gaitR, Gait training including reactive balance component; gaitNR, Gait training not including reactive balance component; WBV, Whole body vibration; str, Strength; pw, Power; 3d, 3D exercise; NE, No exercise.

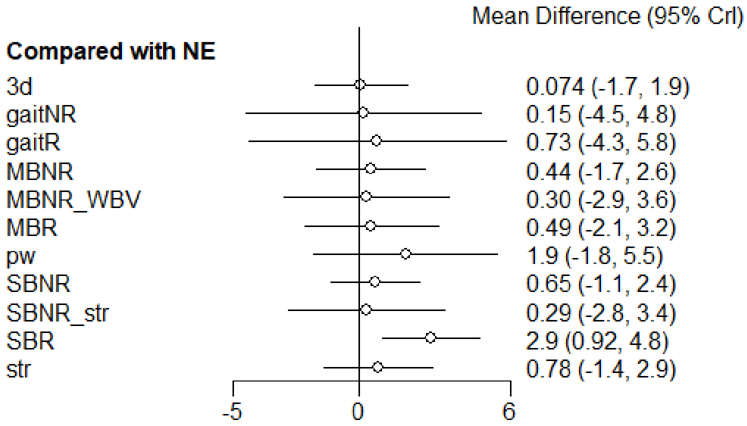
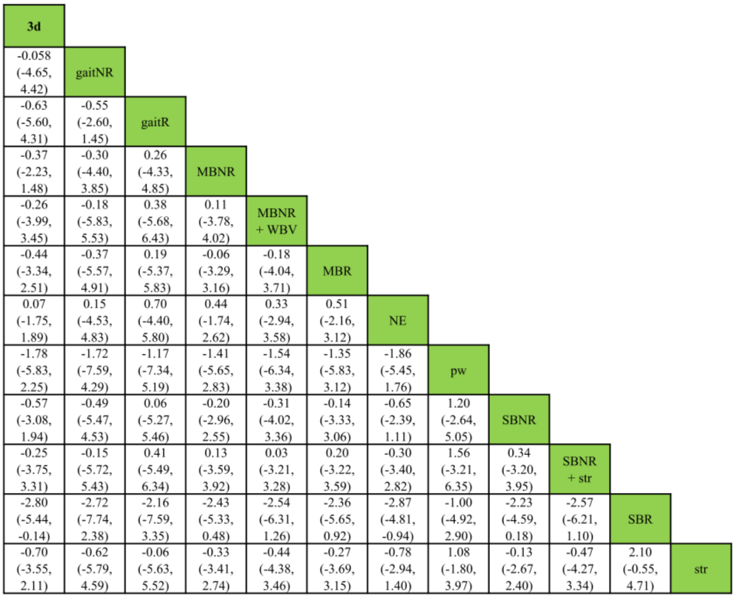


Figure 7: Forest plot of the relative effects of exercise interventions with a no-exercise as a reference group in healthy older adults. SBR, Single balance exercise including reactive balance component; SBNR, Single balance exercise not including reactive balance component; MBR, Multiple balance exercises including reactive balance component; MBNR, Multiple balance exercises not including reactive balance component; gaitR, Gait training including reactive balance component; gaitNR, Gait training not including reactive balance component; WBV, Whole body vibration; str, Strength; pw, Power; 3d, 3D exercise; NE, No exercise.



3d											
-0.058 (-4.65, 4.42)	gaitNR										
-0.63 (-5.60, 4.31)	-0.55 (-2.60, 1.45)	gaitR									
-0.37 (-2.23, 1.48)	-0.30 (-4.40, 3.85)	0.26 (-4.33, 4.85)	MBNR								
-0.26 (-3.99, 3.45)	-0.18 (-5.83, 5.53)	0.38 (-5.68, 6.43)	0.11 (-3.78, 4.02)	MBNR + WBV							
-0.44 (-3.34, 2.51)	-0.37 (-5.57, 4.91)	0.19 (-5.37, 5.83)	-0.06 (-3.29, 3.16)	-0.18 (-4.04, 3.71)	MBR						
0.07 (-1.75, 1.89)	0.15 (-4.53, 4.83)	0.70 (-4.40, 5.80)	0.44 (-1.74, 2.62)	0.33 (-2.94, 3.58)	0.51 (-2.16, 3.12)	NE					
-1.78 (-5.83, 2.25)	-1.72 (-7.59, 4.29)	-1.17 (-7.34, 5.19)	-1.41 (-5.65, 2.83)	-1.54 (-6.34, 3.38)	-1.35 (-5.83, 3.12)	-1.86 (-5.45, 1.76)	pw				
-0.57 (-3.08, 1.94)	-0.49 (-5.47, 4.53)	0.06 (-5.27, 5.46)	-0.20 (-2.96, 2.55)	-0.31 (-4.02, 3.36)	-0.14 (-3.33, 3.06)	-0.65 (-2.39, 1.11)	1.20 (-2.64, 5.05)	SBNR			
-0.25 (-3.75, 3.31)	-0.15 (-5.72, 5.43)	0.41 (-5.49, 6.34)	0.13 (-3.59, 3.92)	0.03 (-3.21, 3.28)	0.20 (-3.22, 3.59)	-0.30 (-3.40, 2.82)	1.56 (-3.21, 6.35)	0.34 (-3.20, 3.95)	SBNR + str		
-2.80 (-5.44, -0.14)	-2.72 (-7.74, 2.38)	-2.16 (-7.59, 3.35)	-2.43 (-5.33, 0.48)	-2.54 (-6.31, 1.26)	-2.36 (-5.65, 0.92)	-2.87 (-4.81, -0.94)	-1.00 (-4.92, 2.90)	-2.23 (-4.59, 0.18)	-2.57 (-6.21, 1.10)	SBR	
-0.70 (-3.55, 2.11)	-0.62 (-5.79, 4.59)	-0.06 (-5.63, 5.52)	-0.33 (-3.41, 2.74)	-0.44 (-4.38, 3.46)	-0.27 (-3.69, 3.15)	-0.78 (-2.94, 1.40)	1.08 (-1.80, 3.97)	-0.13 (-2.67, 2.40)	-0.47 (-4.27, 3.34)	2.10 (-0.55, 4.71)	str

Figure 8: Relative effect estimates with 95% credible intervals of all pairs of exercise interventions in healthy older adults

For the second subgroup analysis regarding the types of reactive balance outcomes, the first type (simulated slip or trip while walking) was analyzed for gaitR versus gaitNR using a multilevel MA due to insufficient trials in other treatment comparisons (i.e., only one direct comparison). The second (simulated forward falls), third (being pushed or pulled), and fourth (movable platform) types were analyzed using NMA. The fifth type (balance test battery) was not analyzed due to the insufficient number of exercise interventions and direct comparisons to establish a network. When a slip or trip was simulated while walking, participants showed greater improvements in measures of balance recoveries after gaitR training versus gaitNR training (SMD = 0.60; 95% CI, .33 to .88). In other types, SBR presented the first or second highest probability of being the best intervention for improving each reactive balance task. The ranking and relative effects of each exercise versus NE are reported in Table 6 and Figure 9, respectively.

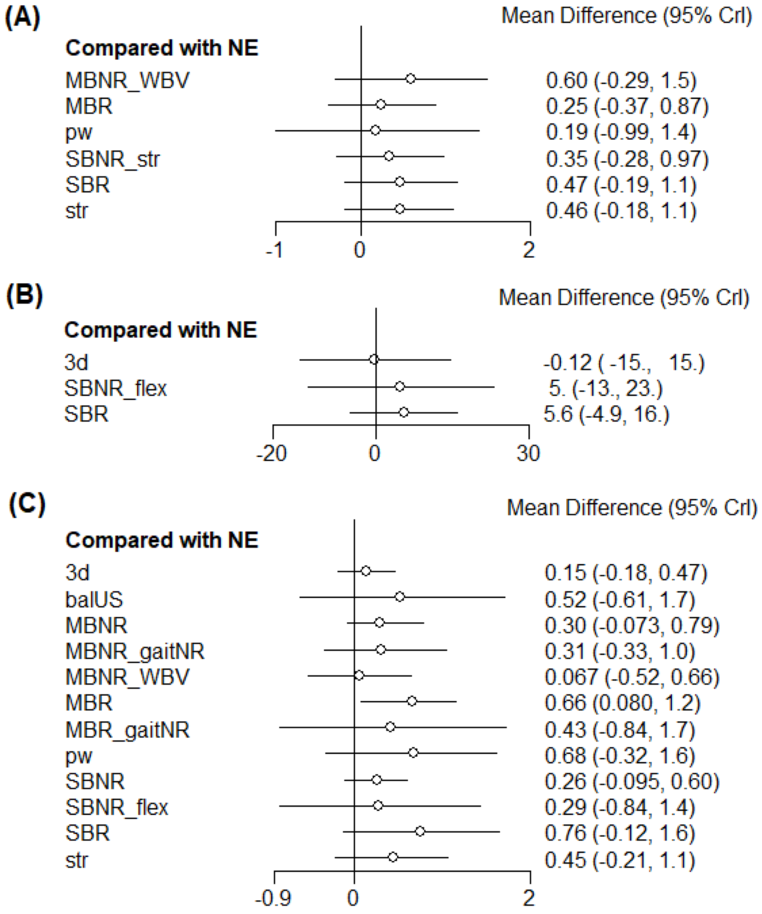


Figure 9: Forest plots of the relative effects of exercise interventions with a no-exercise as a reference group in each reactive balance outcome category. **(A)** Simulated forward falls, **(B)** Being pushed or pulled, **(C)** Movable platform. SBR, Single balance exercise including reactive balance component; SBNR, Single balance exercise not including reactive balance component; MBR, Multiple balance exercises including reactive balance component; MBNR, Multiple balance exercises not including reactive balance component; WBV, Whole body vibration; str, Strength; pw, Power; 3d, 3D exercise; NE, No exercise.

Table 6*:* Ranking of exercise interventions in each reactive balance outcome category. A. Simulated forward falls, B. Being pushed or pulled, C. Movable platform.

A			B			C		
Ranking	Exercise	SUCRA score	Ranking	Exercise	SUCRA score	Ranking	Exercise	SUCRA score
1	MBNR + WBV	0.77	1	SBR	0.73	1	SBR	0.79
2	SBR	0.65	2	SBNR + flex	0.63	2	MBR	0.75
3	Str	0.64	3	3d	0.35	3	pw	0.72
4	SBNR + str	0.52	4	NE	0.30	4	balUS	0.60
5	pw	0.39				5	str	0.58
6	MBR	0.39				6	MBR +gaitNR	0.54
7	NE	0.14				7	MBNR	0.48
						8	MBNR +gaitNR	0.48
						9	SBNR	0.43
						10	SBNR + flex	0.43
						11	3d	0.30
						12	MBNR + WBV	0.25
						13	NE	0.14

SBR, Single balance exercise including reactive balance component; SBNR, Single balance exercise not including reactive balance component; MBR, Multiple balance exercises including reactive balance component; MBNR, Multiple balance exercises not including reactive balance component; WBV, Whole body vibration; str, Strength; pw, Power; 3d, 3D exercise; NE, No exercise.

Discussion

To our knowledge, this study is the first NMA to determine which type of exercise intervention is most effective in improving reactive balance in older adults. In this study, we compared the effects of commonly used exercise interventions on reactive balance in older adults. The NMA was used to analyze the data of 39 RCTs including 1388 participants, which revealed that older adults receiving a balance exercise with a reactive balance component showed the most improvements in reactive balance, followed by power training (second) and gait training with a reactive balance component (third) among 17 different exercise interventions.

The results of this current study highlight the importance of applying the principle of specificity to training interventions designed to improve reactive balance. This is consistent with the hypothesis put forth by Grabiner et al, [56] suggesting that task-specific perturbation training is superior to conventional exercise approaches in improving reactive balance capacity and thus preventing falls [56]. Of the 46 trials in the current study, there were 20 trials including at least one exercise intervention with a reactive balance component, and ten of which utilized the same parameters of postural perturbations during the training and assessment (i.e., task-specific reactive balance training) [34,36,39-43,45-47]. This latter point is especially important given that a specific type of reactive balance exercise has no, or at most a limited transfer effect on non-trained reactive balance tasks [57,58]. The cognitive processes, muscle synergies, and succeeding kinematic strategies to counteract the perturbation are entirely determined by the parameters of the perturbations, such as type, magnitude, direction, and the point of application [56,59,60], and reactive balance improves in the tasks that are specifically trained with the same parameters. That is one of the reasons SBR showed greater improvements than other types of exercises. It seems reasonable to speculate that if all 20 trials used the exact same training and assessment tasks, the performance gains in reactive balance would be even greater. However, the estimates in the second subgroup analyses (i.e., types of reactive balance outcomes) regarding high SUCRA scores of SBR should be interpreted with caution given the small number of trials and several wide credible intervals.

Repeated exposure to specific learning environments, therefore, leads to specific motor adaptation and learning. Motor adaptation is a learning process in which the nervous system learns how to predict and cancel impacts of a novel environment (e.g., perturbation), and ultimately maximize performance in that environment [61]. The cerebral cortex plays a key role in the acquisition and facilitation of balance recovery skills [62,63]. Through repeated exposure to a postural perturbation, our sensorimotor system learns (e.g., procedural learning) internal models for the sensorial prediction and motor commands and uses the learned models for an efficient and optimized movement plan [61], ultimately improving compensatory reactions in older adults [12,64]. If mechanical perturbations transpire in consistent patterns with regards to the timing, magnitude, type, and direction, those who have undergone training using the same perturbation system could employ proactive (anticipatory) postural adjustments (i.e., feedforward control in anticipation of or before a postural perturbation) [65-67]. Utilization of proactive postural adjustments, facilitated by the repeated exposure to the perturbation, significantly reduces the need for compensatory adjustments after a perturbation [68]; thus, the predictability regarding the perturbation and reactive balance task ultimately imparts greater adaptability and controllability. Such motor training is capable of altering corticospinal excitations and reorganizing motor maps and synaptic changes in the cerebral cortex, which ultimately facilitates the acquisition of a specific balance recovery skill [56,62], and the neuroplastic changes after training offer revealing clinical insights. However, when the patterns of a perturbation unpredictably change, the proactive postural adjustments, that are strictly relying on prior experience, can be deteriorated, which may compromise application to real-world falls where people rarely know in advance how and when they will get perturbed. Thus, a perturbation during training needs to be offered in various patterns to maximize the unpredictability and prepare older adults for the unpredictable nature of real-world falls [58]. Further, to promote motor adaptation and learning, the elements of the training regimen should be properly determined first, and the challenge should be increased by adjusting the parameters of the perturbation, complexity of the context, and cognitive processing demands [58].

The greatest effect of SBR and relatively less effective multicomponent exercise interventions can be further scrutinized via several critical principles of exercise training including volume, intensity, and frequency. Training volume is largely determined by the time commitment (duration) of the training. However, the total duration and frequency of the interventions are broadly ranged across the included studies as previously reported, and the average duration of each training session was 52.2 ± 19.7 min. If an intervention included multiple types of exercises in a single session, the intervention may lack the critical time needed to focus on reactive balance training. According to Burgomaster et al. [69], low-volume, high-intensity training and high-volume, low-intensity training induce comparable changes in selected whole-body and skeletal muscle adaptations when the frequencies and the total durations are identical [69,70]. Thus, if lack of time is a barrier to satisfying the need for reactive balance training, the intensity aspect of the training should be considered as a way to compensate for the deficit and induce targeted changes in reactive balance. Further, it is encouraging that Bhatt and Pai have demonstrated significant improvements in reactive balance performance after a single high-intensity training with task-specific postural perturbations [71]. This is particularly noteworthy given that such minimal training effects were retained for several months when properly selecting the intensity and specificity of the training despite the relatively small total volume. Thus, future trials may wish to take account of the aforementioned factors, including specificity, volume, and intensity of the training to maximize the time-effective transfer to real-world scenarios.

Lastly, given the high ranking of power training, the probable inter-relation with reactive balance is clinically notable. In situations where a mechanical perturbation is applied and a fall begins, the rate of torque development in the lower or upper extremity joints with intersegment coordination has been considered as a critical determinant of balance recovery by taking a step or reach to grasp [72]. Aging inherently brings a loss of motor neurons, associated with apoptosis, and reduction and denervation of muscle fibers, specifically related to type II muscle fibers. These changes lead to a decrease in the muscles' capacity to produce maximum muscle strength, power, and rate of force development [73]. In general, fallers generate less muscle power than non-fallers, and older adults generate less power than young adults [72,74]. By utilizing the comparability between muscle power and reactive balance, such as forceful and controlled movements with high velocity, all power training groups in the current analysis demonstrated improvements in measures of reactive balance. There are a handful of studies investigating the correlations between muscle power and reactive balance performances [75]; however, the effectiveness of power training on reactive balance has been explored only in a few, recent trials [76-78]. The results of this study may have implications for future directions in assessing the relationship between muscle power and reactive balance.

Given that the vast majority of falls occur while walking [9,79-82], training to counter postural perturbations while walking is imperative. However, the ranking of gaitR was relatively lower than SBR. Because gaitR was only compared with gaitNR in the network, the ranking was dominantly determined by indirect evidence. Standard errors from indirect evidence are greater than those from direct evidence, which represents the lower accuracy of an estimate [20]. Thus, the indirect evidence should be interpreted with caution, and more RCTs with direct comparisons between gaitR and other exercises may guarantee more accurate posterior distributions and the ranking of gaitR.

Clinical Implications

Considering the findings of this study, it would be advisable for clinicians to preferentially include reactive balance training in line with specifically targeted context, direction, and type of postural perturbations, and power training as a secondarily or complementary approach to improve reactive balance in older adults irrespective of their clinical classifications.

Multicomponent exercise interventions not including a reactive balance component may not bring as marked changes in reactive balance as a single reactive balance training does, whereas they still have benefits regarding general health and physical functioning. The possibility of task-specific training adaptations with balance training using external mechanical perturbations has far-reaching clinical and research implications. In fact, beyond simply training one specific type of balance reaction (e.g., a slip), future trials may wish to include multiple types of reactive balance tasks in various simulated contexts that are likely to occur in daily life and appraise the generalizability and ecological validity of the trained tasks from a long-term perspective. Moreover, the addition of power training may synergize the effects on functional reflex activities as well as general functional capabilities needed for daily tasks and reducing falls in older adults.

Strengths and Limitations

One of the major strengths of the current study is the use of a NMA. The notable advantage of a NMA over a conventional pairwise meta-analysis is the ability to allow for indirect comparisons, accounting for the effects of multiple interventions in a single statistical model [26]. Thus, a NMA concurrently summarizes both direct and indirect comparisons between multifarious interventions and enables more complex statistical models and broader interpretation. Random-effects models attempt to generalize the results beyond the trials included in the NMA with an assumption that the selected trials are random samples from a larger population [83]. Accordingly, the use of a NMA with a random-effects model in this study enhances the applicability and generalizability of study findings. It should be noted that in general, the indirect estimates tend to have greater variance than direct estimates, and the reliability of the indirect estimates are influenced by the number of direct estimates in the network [16]. Future meta-analyses may wish to assess publication bias and heterogeneity with a greater number of trials in each direct comparison.

The interpretations of the results in the current study are limited due to small sample sizes and the existence of the probable risk of bias in the included studies. For example, only two trials included more than 100 total participants [35,84]. Furthermore, there was heterogeneity in participants and exercise interventions. For example, there were several distinct disease groups, and the frequency and duration were set differently for various exercise interventions pooled together. With further trials, future reviews may wish to break down the analyses on the basis of hypothetical effect modifiers, such as detailed age and disease groups, baseline functional capacities, or dosage of intervention, for more specific clinical decisions. Also, the low number of trials per comparison precluded investigating sources of publication bias and heterogeneity, and the overall risk of bias was appraised as some concern or high-risk level. Thus, a comprehensive search of published and unpublished works of literature with a paired screening process was conducted to guarantee all available literature was identified to reduce the potential risk of publication bias. Considering the number of trials per each direct comparison, sample sizes, and overall risks of bias, the results of our analyses may as such guide future research. Despite the aforementioned limitations, we believe that this systematic review with a NMA shed light on better understanding effective interventions for reactive balance in older adults via more comprehensive and inclusive analyses of available literature.

Conclusions

In conclusion, our NMA indicates that SBR, which simulates a real-life fall scenario and induces a specific balance recovery, is generally more efficacious in improving reactive balance than any other exercise intervention in older adults. Importantly, power training also appears to have greater impacts on reactive balance than other exercise interventions. Our results highlight the importance of task-specific exercise interventions with respect to the targeted postural perturbation and reactions. More trials with high methodological quality, low risk of bias, larger samples, and older adults with a specific disease or disability need to be conducted to construct a comprehensive literature basis, which would facilitate a more thorough NMA. The findings of this study could be used to design exercise-based interventions for improving reactive balance in older adults.

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Supplementary Material

Supplementary Table 1: List of all included studies (n = 46).

Allin, L. J., Brolinson, P. G., Beach, B. M., Kim, S., Nussbaum, M. A., Roberto, K. A., et al. (2020). Perturbation-based balance training targeting both slip- and trip-induced falls among older adults: a randomized controlled trial. BMC geriatrics 20, 205. doi:10.1186/s12877-020-01605-9.

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Supplementary Table 2: Summary of outcome measures and main findings.

Study	Reactive balance outcome measures	Outcome variables	Main findings
Allin 2020	Laboratory-induced slip or trip while walking	Slip: peak slip speed, slip distance, non-slipping toe to COM at TD, minimum hip height, margin of stability at TD, velocity of COM relative to BOS at TD, incidence of falls during testing. Trip: trunk angle at TD, recovery step length, minimum hip height, margin of stability, incidence of falls during testing	Regarding slips, several measures of reactive balance and fall incidence were more improved in group 1 versus group 2. No between-group difference regarding trips,
Arampatzis 2011	Simulated forward falls (lean-and-release)	Anterior boundary of the BOS, position of the XCOM, horizontal component of the projection of the COM to the ground, horizontal velocity of the COM, rate of increase of BOS, reaction time, duration until TD, max hip flexion moment, time to max hip moment, rate of hip moment generation, duration of main stance phase	Two exercise groups improved in a similar extent versus group 3.
Arghavani 2020	Pendulum impact received by both hands in the sagittal plane while standing	Muscle onset latencies of TA, MG, RF, BF, RA, ES	Group 1 showed greater rates of progress in all six muscles versus the other two groups. Group 2 showed greater improvements in RF and BF muscles versus group 3.
Beling 2009	Adaptation Test (toes-up and toes-down surface perturbation while standing)	Classified: Adaptive = no falls and less than 2/5 trials in abnormal range; Maladaptive = no falls and greater than 2/5 trials in abnormal range; Unable to Adapt = any fall during the trials	Group 1, but not group 2, showed improvements in both conditions.
Bieryla 2007	Simulated trip while walking	Maximum trunk angle, time to maximum trunk angle, maximum trunk angular velocity, time to maximum trunk angular velocity, trunk angle at foot contact, trunk angle velocity at foot contact, minimum hip height, COM-to-foot distance at foot contact	Group 1 showed a greater reduction in maximum trunk angle and time to maximum trunk angle and increased minimum hip height versus group 2.
Bogaerts 2007	Motor Control Test (unexpected forward and backward platform translation while standing), Adaptation Test	Motor Control Test (latency of reaction, response strength), Adaptation Test (capacity to minimize postural sway after the perturbation)	Motor Control Test: Exercise had no effect on latency for any conditions. Adaptation test: Group 1 showed a significant improvement in the toes-down condition. No group difference in the toes-up condition.
Cabrera-Martos 2020	Mini-BESTest	Reactive postural balance section	Group 1 showed a greater improvement versus group 2.
Cherup 2019	Dynamic posturography (a platform randomly moving in all three planes)	Comprehensive DMA score, time remained on the platform	No significant between-group differences in all outcomes.
Chyu 2010	Motor Control Test, Adaptation Test	Motor Control Test (latency of reaction, magnitude of the postural righting response), Adaptation Test (capacity to minimize postural sway after the perturbation)	No significant between-group differences in all outcomes.
Donath 2016	Platform perturbation (posterior direction) while kneeling	Total COP path length displacement	Two exercise groups showed improvements (greater in the balance group). No improvement in NE group.
Gatts 2007	Laboratory-induced slip while walking	Number of trips and heel strikes during testing, medial cross-step distance, shoulder and trunk angles, COM (velocity, path distance in AP, ML, and vertical directions), COP (velocity, path distance in AP and ML directions), COM-COP separation angles	Group 1, but not group 2, showed significantly reduced tripping, medial cross-step distance, increased use of swing leg heel strike, and COM AP path. In addition, group 1 showed a trend toward increased COM-COP AP angular separation at right heel strike.
Gatts 2008	Laboratory-induced slip while walking	Muscle onset latencies, duration of muscle activities, and duration of co-contraction of TA and MG	Group 1, but not group 2, showed significantly reduced TA response time and decreased co-contraction of antagonist muscles of the perturbed leg.
Granacher 2006	Decelerating perturbation while walking on a treadmill	Angular velocity of the ankle and knee joint, reflex activity (decelerating perturbation impulses), muscle onset latencies of TA, PE, and SO	Group 2 showed a decrease in onset latency, an enhanced reflex activity in the prime mover, and a decrease in maximal angular velocity of the ankle joint complex. No significant

			changes in groups 1 and 3.
Granacher 2009	ML perturbation impulse of a swinging platform while standing	Summed oscillations of the swinging platform in AP and ML directions, averaged EMG signals of TA and PE	Neither group showed any significant improvements.
Hamed 2018	Simulated forward falls (lean-and-release)	Limits of stability, margin of stability at release and TD, BOS at TD, duration from release until TD, rate of increase in BOS, maximum voluntary isometric knee extension and ankle plantarflexion moment	Both exercise groups, but not group 3, showed improvements in general.
Hatzitaki 2009	Avoiding pendulum-like obstacle moving toward the participants' face in the sagittal plane without lifting their feet while standing on a platform	Peak of COP amplitude (APA and response phase), time to peak COP (APA and response phase), maximum trunk roll velocity, onset time of the APA	Group 1 showed significantly reduced COP response amplitude and increased maximum trunk roll velocity. APA onset time was significantly smaller for both Group 1 and 2.
Hu 1994	Horizontal platform translations while standing	Frequency of onset of muscles (GA, hamstrings, TA, quadriceps, trunk extensor, trunk flexor, neck extensor, neck flexor), muscle onset latencies, sequence of muscle onsets, averaged integrated EMG amplitude, joint angle patterns	Group 1 showed decreased onset frequency of the antagonist leg muscles, shortened onset latency of the neck flexor muscle, decreased response frequency of antagonist muscles, increased response frequency of the trunk flexor muscles, and decreased maximal excursion of the first trial of the ankle joint rotation versus group 2.
Inacio 2018	Stepping induced by lateral waist-pulls to the side of the limb where the weight was laterally transferred initially (50%, 65% and 80% BW)	Incidence of stabilizing single lateral recovery steps, lift-off time of the stepping foot, downward COM momentum at step lift-off, net hip abduction torque and power during the pre-step weight transfer phase, muscle activation of TFL, Gmed, and ADD	Group 1 showed a significantly increased incidence of stabilizing single lateral steps at 80% body mass pre-load, reduced step lift-off time at 50% body mass, and decreased downward momentum of the body COM at 80% body mass. In addition, group 1 showed increased hip abductor net joint torque, power, and abductor-adductor rate of neuromuscular activation.
Jagdhane 2016	Pendulum impact applied to the shoulders while standing	APA muscle activities or MG, TA, BF, RF, EO	Group 1, but not group 2, showed early onsets of APA activity prior to the external perturbations.
Kim 2010	Laboratory-induced slip while walking	Heel contact velocity, COM velocity, transitional acceleration of the whole body COM, step length, required coefficient of friction (friction demand), slip severity	Decreases in heel contact velocities and the friction demand characteristics and increase in transitional acceleration of the whole body COM in group 1 and 2. No intergroup differences in COM velocity, step length, and slip severity.
Klamroth 2019	Mini-BESTest	Reactive postural balance section	Group 1 showed a greater number of subjects with an improvement in reactive balance versus group 2.
Lacroix 2016	(1) Treadmill perturbation in the transverse plane while standing (2) Clinical push and release test	(1) summed oscillations of the platform in ML and AP directions; and (2) the number of steps and quality of the recovery	Group 1 and 2 showed improvements in the clinical push and release test. No between-group differences in the ability to compensate following platform translations.
Li 2009	Surface tilt perturbation of 18° generating ankle inversion while standing	Muscle onset latencies of RF, ST, gastrocnemius, and TA	Group 1 showed a significant decrease in ST muscle latency versus group2. No between-group differences in other muscles.
Ma 2019	Posterior-to-anterior trunk perturbation	Muscle onset latencies of MH and gastrocnemius, COP path length, and velocity	The muscle onset latency of gastrocnemius was longer in Group 1 versus Group 2. No between-group differences in other outcomes.
Mansfield 2010	Surface translation and/or cable pull (pelvic level): (1) stepping evoked by forward and backward perturbations while standing, (2) stepping evoked by leftward and rightward perturbations while walking in place, (3) grasping evoked by backward perturbations while standing	**All stepping reactions**: frequency of multi-step reactions, **AP stepping reactions**: frequency of extra lateral steps, frequency of reactions with more than two AP steps, foot-off time, foot-contact time, **ML stepping reactions**: frequency of foot collisions, crossover steps, **Grasping reactions**: handrail contact time, biceps muscle onset latency, frequency of grasping errors, **Forward fall stepping reactions**: forward step displacement, lateral step displacement, **Backward fall stepping**	Group 1 showed greater reductions in the frequency of multi-step reactions and foot collisions during surface translations, but not cable pulls. Group 1 showed greater reductions in handrail contact time versus group 2 for cable pulls.

		reactions: backward step displacement, lateral step displacement.	
Marigold 2005	Platform translations (forward and backward directions) while standing	Muscle onset latencies of TA and RF for the forward translations and MG and BF for the backward translations, number of falls during the platform translations	Group 1 showed greater improvements in step reaction time, paretic RF postural reflex onset latency, and the number of induced falls versus group 2.
Morat 2019	Pendular movement of the platform in ML direction while standing	Total postural sway	Group 1 showed an improvement in the total postural sway.
Ni 2014	Dynamic posturography (EO and EC)	DMA score, time on the test, linear and angular displacements in the ML, AP, and up/down directions	Group 2 showed higher DMA scores and shorter time on the test versus group 1.
Ochi 2015	Simulated forward falls (lean-and-release)	spatiotemporal parameters (lift-off time, step time, step length, step velocity, trunk angle at initial lean and foot contact), EMG onset times, timing of first-peak EMG amplitude, and normalized peak EMG amplitude of RF, VL, BF, TA, LG	Both groups showed extended step length and increased peak EMG of knee flexor and extensor muscles. Group 1 showed increased step velocity and peak EMG of the plantar flexors.
Okubo 2019	Laboratory-induced slip or trip while walking	Rate of falls, margin of stability, XCOM position, step length, step height, trunk sway range, slip speed, slip distance	Group 1 showed a lower rate of falls versus group 2. During a trip, group 1's XCoM position was less anterior, the recovery stepping foot was higher, and the trunk sway range was smaller versus group 2. During a slip, group 1 had less posterior XCoM position, shorter backward step length, and smaller trunk sway range versus group 2.
Pamukoff 2014	Simulated forward and lateral falls (lean-and-release)	The largest angle from which the participant could successfully recover their balance	No between-group differences in all outcomes.
Parijat 2012	Laboratory-induced slip while walking	Incidence of falls, slip severity (slip distance and peek sliding heel velocity), joint angles (ankle, knee, hip, and trunk angles at HC, peak angles of ankle, knee, hip, and trunk), peak joint angular velocity (ankle, knee, hip, trunk), muscle activation onset and time to peak activations of MG, TA, MH, and VL, coactivations (peak ankle and knee co-activities, time to peak ankle and knee co-activities), non-slipping foot response time (toe-off, foot-onset, foot down, unperturbed foot reaction time), unperturbed foot reaction time	Group 1 showed greater reductions in the incidence of falls and slip severity (slip distance and peak sliding heel velocity) versus group 2. Group 1 showed proactive adjustments (increased COM velocity and transitional acceleration), and reactive adjustments (reduction in muscle onset and time to peak activations of knee flexors and ankle plantar flexors, reduced ankle and knee coactivation, reduced slip displacement, and reduced time to peak knee flexion, trunk flexion, and hip flexion velocities). Group 1 showed a shorter reaction time of the unperturbed foot versus group 2.
Parijat 2015a	Laboratory-induced slip while walking	Incidence of falls during testing, joint angles (ankle, knee, hip, and trunk angles at HC, peak angles of ankle, knee, hip, and trunk), peak joint angular velocity (ankle, knee, hip, trunk), muscle activation onset and time to peak activations of MG, TA, MH, and VL, coactivations (peak ankle and knee co-activities, time to peak ankle and knee co-activities).	Group 1 showed proactive adjustments (increased trunk flexion at heel contact) and reactive adjustments (reduced time to peak activations of knee flexors, reduced knee coactivation, reduced time to trunk flexion, and reduced trunk angular velocity).
Parijat 2015b	Laboratory-induced slip while walking	Incidence of falls during testing, slip distance, peak sliding heel velocity	Group 1 showed a reduced incidence of falls, slip distance, and peak sliding heel velocity.
Pluchino 2012	Dynamic posturography	DMA score, translational movements (AP, ML, up/down), rotational movements (flexion/extension, lateral flexion, core rotational)	No significant group differences in all outcomes.
Qutubuddin 2007	Dynamic posturography	Adaptation test scores	No significant group differences in all outcomes.
Rieger 2020	Treadmill perturbation in AP and ML directions while walking	Deviations of perturbed gait trunk velocity from unperturbed gait	Both groups showed improvements in AP and ML directions, but no group differences were reported.
Rossi 2014	Platform translations in forward and backward directions while standing	EMG amplitude of RF, VMO, ST, TA, MG, and SO in the early (0-200 ms), intermediate (201-400 ms), and late (401-600 ms) phases	Greater amplitude for group 1 than for group 2 after training for the TA, MG, and SO muscles at the early phase and for the SO muscle at the intermediate phase. No difference in the late phase.
Santos 2017	BESTest	Reactive postural responses section	No significant group difference.

Schlenstedt 2015	Platform translations in forward and backward directions while standing	COM displacement	No significant group difference.
Shimada 2003	Manual perturbation test (shoulder was pulled backwards)	Responses were scored (0-2)	No significant group difference.
Sohn 2015	Laboratory-induced slip while walking	COP area and distance, fall frequency	Group 1 and 2 showed improvements in all outcomes in comparison to group 3.
Thomas 2016	Platform translations in ML direction while standing (tandem stand and one-leg stand)	Time of standing on the moving platform without holding to the handrail, accumulated accelerations	Both groups showed improvements in the time of standing and accumulated accelerations. No group differences were reported.
Wang 2019	Laboratory-induced slip while walking	Slip recovery classification (fall, backward loss of balance, or full recovery), dynamic stability control (proactive stability control at slipping foot TD and reactive stability control at recovery foot lift off)	Group 1 showed fewer falls and greater proactive and reactive stability versus group 2.
Wolf 1997	Angular perturbation (toes up and toes down) of a platform while standing on the Chattexc Balance System	Dispersion measures, measures of center of balance in X and Y axes	Dispersion under toes up and down conditions were reduced substantially in group 1 versus group 2 and 3. Center of balance in X axis under toes up condition showed a greater decrease in group 1 versus group 2 and 3. Center of balance in Y axis increased in group 3.
Wooten 2018	Dynamic posturography	DMA score, total time on the test	No significant group differences.

COM, center of mass; XCOM, extrapolated center of mass; COP, center of pressure; TD, touch down; HC, heel contact; BOS, base of support; EMG, electromyograph; TA, tibialis anterior; MG, medial gastrocnemius; LG, lateral gastrocnemius; SO, soleus; PE, peroneus; RF, rectus femoris; VL, vastus lateralis; VMO, vastus medialis oblique; BF, biceps femoris; MH, medial hamstring; ST, semitendinosus; TFL, tensor fascia latae; Gmed, gluteus medius; ADD, adductor magnus; RA, rectus abdominis; EO, external oblique; ES, erector spinae; AP, anteroposterior; ML, mediolateral; APA, anticipatory postural adjustment; EO, eyes open; EC, eyes closed; DMA, Dynamic motion analysis; BW, body weight.

Supplementary Table 3: Summary table of the reviewers' judgements for the risk of bias of each study.

Study	Randomization process	Deviations from the intended interventions	Missing outcome data	Measurement of the outcome	Selection of the reported result	Overall
Allin 2020	Some concerns	Low	Low	Low	Some concerns	Some concerns
Arampatzis 2011	Some concerns	Low	High	Low	Some concerns	High
Arghavani 2020	Some concerns	Low	High	Low	Some concerns	High
Beling 2009	Some concerns	Low	Low	Low	Some concerns	Some concerns
Bieryla 2007	Some concerns	High	Low	Low	Some concerns	High
Bogaerts 2007	Some concerns	Low	High	Low	Some concerns	High
Cabrera-Martos 2020	Low	Low	Low	Low	Low	Low
Cherup 2019	Some concerns	Low	High	Low	Some concerns	High
Chyu 2010	Low	Some concerns	Low	Low	Some concerns	Some concerns
Donath 2016	Low	Some concerns	High	Low	Some concerns	High
Gatts 2007	Some concerns	Some concerns	High	Low	Some concerns	High
Gatts 2008	Some concerns	Some concerns	High	Low	Some concerns	High
Granacher 2006	Some concerns	Low	Low	Low	Some concerns	Some concerns
Granacher 2009	Some concerns	Low	Low	Low	Some concerns	Some concerns
Hamed 2018	Low	Some concerns	Low	Low	Some concerns	Some concerns
Hatzitaki 2009	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns
Hu 1994	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns
Inacio 2018	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns
Jagdhane 2016	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns
Kim 2010	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns

Klamroth 2019	Some concerns	Some concerns	High	Low	High	High
Lacroix 2016	Low	Some concerns	High	Low	Some concerns	High
Li 2009	Some concerns	Some concerns	High	Low	Some concerns	High
Ma 2019	Low	Some concerns	Low	Low	Low	Some concerns
Mansfield 2010	Low	Some concerns	High	Low	Low	High
Marigold 2005	Low	Low	High	Low	Some concerns	High
Morat 2019	Some concerns	Low	High	Low	Some concerns	High
Ni 2014	Some concerns	Some concerns	High	Low	Some concerns	High
Ochi 2015	Some concerns	Low	Low	Low	Some concerns	Some concerns
Okubo 2019	Low	Some concerns	Low	Low	Low	Some concerns
Pamukoff 2014	Some concerns	Low	High	Low	Some concerns	High
Parijat 2012	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns
Parijat 2015a	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns
Parijat 2015b	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns
Pluchino 2012	Low	Low	High	Low	Some concerns	High
Qutubuddin 2007	Some concerns	Some concerns	High	Low	Some concerns	High
Rieger 2020	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns
Rossi 2014	Some concerns	Some concerns	Low	Low	Low	Some concerns
Santos 2017	Low	Low	High	Low	Low	High
Schlenstedt 2015	Some concerns	Some concerns	High	Low	Low	High
Shimada 2003	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns
Sohn 2015	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns
Thomas 2016	Some concerns	Some concerns	Low	Low	Some concerns	Some concerns
Wang 2019	Some concerns	Low	Low	Low	Low	Some concerns
Wolf 1997	High	Some concerns	High	Low	Some concerns	High
Wooten 2018	Some concerns	Low	High	Low	Some concerns	High