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Balance Control and Exercise-Based Interventions in Older Adults

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BALANCE CONTROL AND EXERCISE-BASED INTERVENTIONS IN OLDER ADULTS

by

Youngwook Kim

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Disability Disciplines

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UTAH STATE UNIVERSITY
Logan, Utah

2021

ABSTRACT

Balance Control and Exercise-Based Interventions in Older Adults

by

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Utah State University, 2021

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Department: Kinesiology and Health Science

Balance and gait disorders are the leading cause of falls in older populations, and exercise is emphasized as the most crucial element of fall prevention strategies. Aquatic exercise is broadly used in various clinical and research settings as an alternative to land-based exercises attributable to the physical properties of water and the consequential benefits for various clinical populations as well as healthy populations. However, the effects of different exercise environments (aquatic versus land) or types of exercise (e.g., gait, strength, or power training) on balance in older adults have not been methodically examined. The purpose of this dissertation was, therefore, to (1) determine effect size estimates between aquatic and land exercises in each category of dynamic balance, and (2) calculate relative effects and induce rankings of different exercise-based interventions for improving reactive balance in older adults. In study 1, 11 studies comprising 372 participants were included, and the effects between aquatic and land exercises were compared using a systematic review with a meta-analysis. Study 2 consisted of 46 studies with 1745 older adults, and comparative effects of all previously used exercise-based interventions on reactive balance were analyzed using a systematic review with a network meta-analysis. The findings demonstrated that (1) aquatic and land exercises comparably improved all categories of dynamic balance measures in older adults, and (2) a single reactive balance exercise, followed by power training, was the most effective intervention to improve reactive balance in the comprehensive older population as well as the heathy older population. These findings will give older adults more extensive options as to the exercise environments, and signify the importance of specificity and volume of balance training in older adults.

(148 pages)

PUBLIC ABSTRACT

Balance Control and Exercise-Based Interventions in Older Adults

Youngwook Kim

Loss of balance and consequential falling, caused by natural degenerations in the sensory and motor systems with aging, are critical issues that require constant research exploration to ultimately improve the quality of life in older populations. Balance can be simply classified into static and dynamic balance, and the latter is more associated with common causes of falling in older adults. There are numerous ways to improve dynamic balance, and exercise training has been considered the most beneficial intervention for that purpose. Specifically, aquatic exercises have been suggested as a promising modality because several properties of water, including buoyance and hydrostatic pressure, impart direct benefits to older adults during the exercise. However, it is still inconclusive whether aquatic exercises are more effective than land exercises at improving dynamic balance.

Further, slips and trips are the most predominant causes of falls in older adults, and they often require a rapid, accurate action to avoid a potential fall. This process is called reactive balance (i.e., compensatory balance reaction). It also can be enhanced by exercise interventions; however, it is unclear what type of exercise is most effective at improving reactive balance. In this dissertation, we compared the impacts of exercise environments on dynamic balance, and then explored what type of exercise intervention improves reactive balance the most in older adults.

These studies revealed that both aquatic and land exercises have equivalent effects on improving dynamic balance, and reactive balance improved most successfully after one or more reactive balance exercises were provided. In addition, power training was the second most effective intervention for improving reactive balance. The findings from this dissertation suggest that when exercise-based interventions are used to improve dynamic balance, the exercise environments can be selected based on the purpose of the intervention or each participant's subjective decision. Moreover, practitioners may wish to implement task-specific reactive balance training on the preferential basis for the intervention aiming at reactive balance. Also, power training, which reflects the mechanism of the targeted reactive balance task, can be jointly or adjunctly utilized to improve reactive balance, which is critical for decreasing falls in older adults.

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Youngwook Kim

CONTENTS

Page

ABSTRACT ... iii

PUBLIC ABSTRACT ... v

ACKNOWLEDGMENTS ... vii

LIST OF TABLES ... x

LIST OF FIGURES ... xi

CHAPTER I INTRODUCTION ... 1

- Background ... 1
- Objectives ... 6
- Structure of Dissertation ... 7

CHAPTER II A SYSTEMATIC REVIEW AND META-ANALYSIS COMPARING THE EFFECT OF AQUATIC AND LAND EXERCISE ON DYNAMIC BALANCE IN OLDER ADULTS ... 8

- Abstract ... 8
- Background ... 10
- Methods ... 12
- Results ... 17
- Discussion ... 29
- Conclusion ... 36

CHAPTER III COMPARATIVE EFFECTS OF EXERCISE INTERVENTIONS ON REACTIVE BALANCE IN OLDER ADULTS: A SYSTEMATIC REVIEW AND NETWORK META-ANALYSIS ... 38

- Abstract ... 38
- Introduction ... 40
- Methods ... 43
- Results ... 49
- Discussion ... 62
- Conclusions ... 68

CHAPTER IV GENERAL DISCUSSION AND CONCLUSIONS 69
REFERENCES.. 74

APPENDICES.. 91

Appendix A. PRISMA for Network Meta-Analyses (PRISMA-NMA) 92
Appendix B. Definitions of exercise types.. 97
Appendix C. List of all included studies 100
Appendix D. Characteristics of participants 106
Appendix E. Summary of exercise interventions.. 109
Appendix F. Summary of outcome measures and main findings 112
Appendix G. Summary table of the reviewers’ judgements for the risk of bias of each study 120
Appendix H. Relative effect estimates with 95% credible intervals of all pairs of exercise interventions... 123
Appendix I. Relative effect estimates with 95% credible intervals of all pairs of exercise interventions in healthy older adults 125
Appendix J. Permission-to-use letters.. 127

CURRICULUM VITAE 131

LIST OF TABLES

Page

Table 2-1 Characteristics of participants and exercise environments 19

Table 2-2 Summary of exercise program 21

Table 2-3 Outcome measures and summary of main findings of all selected studies 22

Table 3-1 Exercise types 45

Table 3-2 Ranking of exercise interventions 54

Table 3-3 Ranking of exercise interventions in healthy older adults 58

Table 3-4 Ranking of exercise interventions in each reactive balance outcome category. A. Simulated forward falls, B. Being pushed or pulled, C. Movable platform 60

LIST OF FIGURES

Page

Figure 2-1. PRISMA flow diagram of article selection process 18

Figure 2-2. Risk of bias of the included studies. (A) Risk of bias graph, (B) Risk of bias summary. Green, low risk; yellow, somewhat concerns; red, high risk. D1, Randomization process; D2, Deviation from intended interventions; D3, missing outcome data; D4, measurement of outcome; D5, selection of the reported result; Overall, overall bias 25

Figure 2-3. Funnel plot for all of the meta-analyses 26

Figure 2-4. Forest plot of comparison: AE versus LE. (A) Dynamic steady-state balance, (B) Proactive balance, (C) Balance test batteries 28

Figure 2-5. Results of sensitivity analyses. (A) Dynamic steady-state balance, (B) Proactive balance, (C) Balance test batteries 29

Figure 3-1. PRISMA flow diagram of study selection 50

Figure 3-2. Summary of the distributions of the reviewers' judgements across the studies for each risk of bias domain 52

Figure 3-3. 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 53

Figure 3-4. 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 56

Figure 3-5. 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 57

Figure 3-6. 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 59

Figure 3-7. 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 61

CHAPTER I

INTRODUCTION

Background

Balance control is a construct that is critical to all aspects of successful human movement including elite sports performance on one end of the spectrum and fall risk in the elderly on the other end of the spectrum (Ganz & Latham, 2020; Hrysomallis, 2011; Y. Kim, Lee, et al., 2020). While the term balance has no universally accepted definition despite its widespread use in the literature, there is a universally accepted mechanical definition of the term. Mechanically, balance is defined as a condition when all resultant loads (forces and moments) acting on and within a body are zero (in equilibrium) (K. Berg, 1989; Pollock et al., 2000). A resistance to linear and angular accelerations that may disrupt equilibrium is referred to as stability (K. Berg, 1989; Pollock et al., 2000). Different mechanical factors affect a body's stability and include mass, friction, center of gravity location, and base of support.

Balance control, a term used in various clinical and research areas, describes how our central nervous system garners and interprets sensory information and generates adequate motor output to maintain and control balance (Ivanenko & Gurfinkel, 2018). In other words, balance control is supported by a complicated interaction of musculoskeletal and neural systems (Shumway-Cook & Woollacott, 2017). The musculoskeletal components include muscle properties and biomechanical relationships among linked body segments, and the neural components comprise the sensory (visual, vestibular, and somatosensory systems) and motor systems, as well as higher-level cognitive processes (Shumway-Cook & Woollacott, 2017). To enable timely and appropriate balance control, multisensory integration that includes information from the tasks and environmental factors is critical for appropriate neuromuscular activations. Specifically, the magnitude and quality of multisensory integration and the accuracy of balance control are associated with fall risks in elderly populations (Mahoney et al., 2019; Osoba et al., 2019).

Age-related neurophysiological changes inherently bring degenerations in the sensory and motor systems, which in turn impairs balance and increases the risk of falls (Mahoney et al., 2019; Osoba et al., 2019). It is reported that approximately 34% of community-dwelling older adults have balance or gait problems, and the proportion increases with age (Değer et al., 2019; Jia et al., 2019). Balance problems are associated with functional limitations, incidence of falls, health-related quality of life, substantial medical costs, and quality-adjusted life years (Jia et al., 2019; Lin & Bhattacharyya, 2012). Therefore, balance-related physical functions are recognized as an important consideration in the elderly. Land-based exercises, regardless of the types such as resistance strengthening, balance, aerobic, or endurance, have been broadly executed as an effective intervention for improving balance and mitigating the risk of falls in older adults (Cadore et al., 2013; Karinkanta et al., 2015; Lesinski et al., 2015). Notwithstanding the evident effectiveness of land-based exercises, older adults report limitations or avoidance of physical activity due to pain, disease, or fear of falling, which is significantly associated with kinesiophobia, referring to excessive, devastating, irrational, and debilitating fear of movement or activity emanated from the belief of fragility and vulnerability to injury or reinjury (Kader et al., 2016; Kori, 1990; Larsson et al., 2016).

Aquatic environments have been utilized as a safe, effective, and comfortable exercise medium for older adults, especially in older adults with kinesiophobia or disease (Y. Kim, Vakula, et al., 2020; Waller et al., 2016). The physical properties of water make aquatic exercise unique, and thus an adequate understanding of how the static and dynamic properties of water affect human movement during water immersion is essential to the prescription of more efficacious aquatic exercise programs. The buoyancy of water provides a low-gravity 'like' environment with an upthrust effect, which consequently allows all motions to be performed with a lower perceived effort (Kisner et al., 2017). The viscosity of water generates resistive drag force against the direction of motion, and it can be utilized to modulate the intensity of the exercise by changing the velocity or surface area of the body part moving through water (Kisner et al., 2017; Severin et al., 2016). Hydrostatic pressure, which increases approximately 981.0 Pa (73.5 mmHg) per meter, exerts a compressive force on the body (Severin et al., 2016). In chest-deep thermoneutral water, the pressure assists venous return and centralizes peripheral blood flow, which enhances cardiovascular performance and musculoskeletal functions (Denning et al., 2012) and facilitates cerebral cortex activity in both sensory and motor areas (Sato et al., 2012). Moreover, water conducts heat 25 times faster than air (Kisner et al., 2017), and the heat capacity of water (pure liquid water = $4.182\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$) is greater than air (1:0.001) as well as the human body tissues (1:0.83) (Becker, 2009; Kisner et al., 2017; Pendergast et al., 2015; Severin et al., 2016). Differences in temperature between an immersed body and the surrounding water accordingly make the body equilibrates faster than water does (Becker, 2009). Thus, the appropriate setting of the water temperature in regards to the age, clinical conditions, type and intensity of aquatic exercises, and the purpose of treatment may ensure the safety of participants and create synergy effects of the aquatic exercises (Aquatic Exercise Association, 2017). Using the abovementioned properties of water, aquatic exercises have been broadly carried out, and the positive effects on balance have been demonstrated in various elderly populations, such as Parkinson's disease (Pérez-de la Cruz, 2018), osteoporosis (Aveiro et al., 2017), peripheral neuropathies (Zivi et al., 2018), heart failure (Adsett et al., 2017), osteoarthritis (Arnold & Faulkner, 2010), and healthy older adults (Bergamin et al., 2013).

First, there is a need to systematically examine the effects of aquatic exercise on balance in older adults to corroborate the beneficial effects of the aquatic environment. According to Shumway-Cook and Woollacott (2017), balance should be classified into several different concepts because it is considerably task-specific and includes the following: static steady-state balance, dynamic steady-state balance, proactive balance, and reactive balance (Shumway-Cook & Woollacott, 2017). When we simply classify balance into static and dynamic balance, the latter is more related to activities of daily living and various functional movements. Effects of land-based balance exercises on balance performance in older adults in regards to the aforementioned balance categories have been reported (Lesinski et al., 2015). Of note, land-based exercises have shown to be effective in improving dynamic balance-related measures, such as tasks in the dynamic steady-state balance, proactive balance, and reactive balance. However, none of the previous research has systematically reviewed or analyzed the effects of aquatic exercises on dynamic balance in older adults.

To the best of our knowledge, none of the previous randomized controlled trials have investigated the effects of aquatic-based exercises on reactive balance in older adults. To recover from a postural perturbation, such as slips and trips that contribute to a substantial percentage of falls in older adults (W. P. Berg et al., 1997), and prevent a fall, the execution of rapid, timely, and accurate compensatory reactions, mostly in the form of stepping or grasping, is imperative. Exercise-based interventions with learning paradigms and motor adaptations that utilize the mechanisms of targeted patterns of reactive balance control may enhance the recovery performances in daily life and ultimately reduce the risk of falling in older adults (Bohm et al., 2015). According to recent reactive balance studies, motor skills acquired from training are transferred to an untrained task to a limited degree (Harper et al., 2021). Nonetheless, a broad range of exercise-based interventions, such as static balance exercise, gait training, slow resistance training, power training, Tai Chi, and Pilates (Cherup et al., 2019; Donath et al., 2016; S. K. Gatts & Woollacott, 2007; Hu & Woollacott, 1994; Rieger et al., 2020), have been implemented, and each of the exercises demonstrated positive effects on reactive balance despite the absence of any postural perturbations during training. Further, it is still inconclusive what type of exercise-based intervention improves reactive balance most effectively, which is of the essence for future research targeting reactive balance in this population. Given the advantages of an aquatic environment as an exercise medium, exercises during water immersion may bring more positive impacts on reactive balance. Thus, there is a need for a thorough and extensive examination of the effects of different types of exercises on reactive balance to design more efficacious aquatic exercise programs aiming at reactive balance.

All exercise intervention programs utilized in the entire previous randomized controlled trials can be compared in one statistical model using a network meta-analysis. Network meta-analysis (NMA), also known as mixed treatment comparison or multiple treatment comparison, is a generalization of pairwise meta-analysis, which combines direct and indirect evidence on treatment effects (Schwarzer et al., 2015). For example, when there are two studies with the first one including interventions A and C and the second one including interventions B and C, the effect sizes can be calculated from each direct comparison between two different interventions. In this case, such studies also facilitate indirect comparison of interventions A and B from the difference between the effect sizes of the aforementioned two direct comparisons. Using the advanced statistical methodology, therefore, a single network meta-analysis model can include more than two treatments in a structure of “Network” and incorporate all the available data in a coherent and internally consistent manner. Also, NMA can be used to estimate which is the most effective of all interventions in the network, that is critical for future clinical decision makings.

Objectives

The general purpose of this dissertation is to appraise prior evidence regarding the effects of exercise interventions on different categories of balance in older adults in relation to the exercise environments (e.g., water and land) or exercise types (e.g., resistance exercise, balance training, aerobic exercise). To accomplish the general purpose, two linked studies, each presented in individual chapters, were conducted with specific objectives described below:

Chapter 2: A systematic review and meta-analysis comparing the effect of aquatic and land exercise on dynamic balance in older adults

Objective: To compare the effectiveness of aquatic exercises to land exercises on dynamic balance in older adults

Chapter 3: Comparative effects of exercise interventions on reactive balance in older adults: A systematic review and network meta-analysis

Objective: To appraise comparative effects of all exercise interventions on reactive balance in older adults

Structure of Dissertation

This dissertation is comprised of one systematic review with meta-analysis and another systematic review with network meta-analysis. First, in chapter 2, a systematic review with meta-analysis was conducted to describe the comparative effects of aquatic versus land exercise on dynamic balance in older adults. In chapter 3, a systematic review with a network meta-analysis was carried out to assess the relative effects of all different exercise-based interventions on reactive balance in older adults. Lastly, chapter 4 includes a summary of the findings from the two systematic reviews with meta-analysis and network meta-analysis, practical applications, and suggestions for future research.

CHAPTER II

A SYSTEMATIC REVIEW AND META-ANALYSIS COMPARING THE EFFECT OF AQUATIC AND LAND EXERCISE ON DYNAMIC BALANCE IN OLDER ADULTS

This chapter comprises the following manuscript published in BMC Geriatrics:

Kim, Y., Vakula, M.N., Waller, B., Bressel, E. (2020). A systematic review and meta-analysis comparing the effect of aquatic and land exercise on dynamic balance in older adults. *BMC Geriatrics, 20*, 302, https://doi.org/10.1186/s12877-020-01702-9.

Abstract

Background: Balance impairments are the leading causes of falls in older adults. Aquatic-based exercises have been broadly practiced as an alternative to land-based exercises; however, the effects on dynamic balance have not been comprehensively reviewed and compared to land exercises. Thus, the purpose of this systematic review and meta-analysis was to compare the effectiveness of aquatic exercises (AE) to land exercises (LE) on dynamic balance in older adults.

Methods: Electronic databases (PubMed, MEDLINE, CINAHL, SPORTDiscus, psycINFO), from inception to November 2019, were searched. Included studies met the following eligibility criteria: Randomized controlled trials, English language, older adults aged 65 years or older, a minimum of one AE and LE group, at least one assessment for dynamic balance. For the meta-analysis, the effect sizes of dynamic balance outcomes were calculated using a standardized mean difference (SMD) and a 95% confidence interval (CI).

Results: A total of 11 trials met the inclusion criteria, and 10 studies were eligible for the meta-analysis. The meta-analysis presented that older adults in AE groups demonstrated comparable enhancements in dynamic steady-state balance (SMD = -0.24; 95% CI, -.81 to .34), proactive balance (SMD = -0.21; 95% CI, -.59 to .17), and balance test batteries (SMD = -0.24; 95% CI, -.50 to .03) compared with those in LE groups.

Conclusions: AE and LE have comparable impacts on dynamic balance in older adults aged 65 years or older. Thus, this review provides evidence that AE can be utilized as a reasonable alternative to LE to improve dynamic balance and possibly reduce the risk of falls. Considering the equivalent impacts of AE and LE on dynamic balance and additional effects on the reductions of pain and fall risk factors during AE, further research in various clinical populations is needed.

Key Words: older adults; seniors; aquatic exercise; aquatic therapy; balance; dynamic balance; falls; fall prevention

Background

In adults aged 65 years or older, approximately 29% of the population experience at least one fall per year, and the rate of falls and fall-related injuries increase with age (Bergen, 2016). Falls are a common cause of morbidity and mortality including both fatal and non-fatal injuries and poor quality of life (Alamgir et al., 2012; Stevens et al., 2008). Falls often cause substantial medical costs. In 2015, fatal fall-related and non-fatal fall-related injuries cost an estimated $637.5 million and $31.3 billion, respectively (E. R. Burns et al., 2016). Considering the globally increasing proportion of older adults, the medical costs related to falls may constantly increase unless cost-effective interventions are established and implemented.

Exercise interventions have been effective at improving balance and reducing fall risks in older adults (Burton et al., 2015; Chan et al., 2015; Okubo et al., 2017; Sherrington et al., 2017). A Cochrane systematic review by Howe et al. (2011) indicated that exercise on land is the most common form of treatment in older adults to improve balance and reduce fall risk (Howe et al., 2011). However, land-based exercises contain a higher rate of extrinsic fall risk factors (e.g., uneven walking surface) when compared to aquatic exercises, which may, in turn, interrupt the progression of a fall prevention exercise program. This is important to note because extrinsic risk factors account for the majority of all falls (Rubenstein, 2006). These aforementioned limitations associated with the safety issues during land-based exercises are less common in aquatic-based exercise programs (Arnold et al., 2008).

Aquatic exercises have been utilized as an alternative to land-based exercises for older adults that display lower physical activity levels, neuromuscular degeneration, or orthopedic disabilities that affect balance, mobility, and pain (Bressel et al., 2014; Martínez-Carbonell Guillamón et al., 2019; Waller et al., 2016). For this systematic review and meta-analysis, we defined aquatic exercise as any type of exercise performed in water. The buoyant force of water and the hydrostatic pressure/density help participants slow the movement, and additional sensory cues supplied by the viscosity of water facilitate muscle recruitment timing (Morris, 2010). Thus, water provides a safe, low-risk, and supportive training environment, which may be advantageous for older adults to participate in exercise programs without the risk or fear of falling (Bressel, Louder, & Dolny, 2017).

Previous systematic reviews have summarized empirical evidence for aquatic exercises on strength, mobility, flexibility, balance, and various health outcomes in older adults (Batterham et al., 2011; Martínez-Carbonell Guillamón et al., 2019; Waller et al., 2016). Observations from these reviews have indicated that aquatic exercises may improve the aforementioned outcome measures. Specifically, a recent systematic review and meta-analysis summarized statistical evidence for aquatic exercise on dynamic balance for the first time and reported that aquatic exercise significantly improved dynamic balance in older adults with knee or hip osteoarthritis (Zampogna et al., 2020). However, only four studies and one outcome measure (Timed Up and Go test) were included in the meta-analysis, and the population was limited to osteoarthritic patients. Moreover, the results of aquatic exercise were compared to the controls, thus, evidence regarding the effectiveness of aquatic exercises over comparable land-based exercises in older adults is inconclusive. Due to complex environments continuously challenging older adults, various dynamic balance abilities, that can be defined as the ability to control postural stability while in motion (Winter et al., 1990), are critical in this population (Frank & Patla, 2003). Age-related neurophysiological changes commonly lead to balance or gait disorders (Mahoney et al., 2019; Osoba et al., 2019), that cause approximately 17% of falls in older adults (Rubenstein, 2006), and exercise programs in various environments (e.g. aquatic or land) improve dynamic balance and prevent falls (Martínez-Carbonell Guillamón et al., 2019; Thomas et al., 2019). Accordingly, there is a need to more formally quantify the effects of AE on dynamic balance concerning fall prevention protocols. This systematic review and meta-analysis aimed to compare the effects of aquatic exercise (AE) and land exercise (LE) on dynamic balance in older adults aged 65 years or older. The PICO question was as follows: "Are aquatic exercises more effective than land-based exercises at improving dynamic balance in older adults aged 65 years or older?"

Methods

A systematic review of the literature with meta-analysis was conducted in November 2019 to examine the effects of AE on dynamic balance in older adults. The following electronic databases were searched by one reviewer (Y.K.) on November 19th, 2019: PubMed (1965-), MEDLINE (1959-), CINAHL (1984-), SPORTDiscus (1978-), psycINFO (1958-). The databases were examined using the following combination of keywords: (aquatic therapy OR aquatic activity OR aquatic aerobics OR aquaerobics OR aquatic exercise OR aquatic physical therapy OR aquatic physiotherapy OR aquatic rehabilitation OR hydrotherapy OR pool exercise* OR pool therapy OR swimming OR swimming therapy OR water aerobics OR water-based exercise OR water exercise OR water rehabilitation OR water therapy OR water activity OR water sport∗) AND (aged OR older OR elderly OR senior) AND (balance OR postur*). There was no restriction on the publication year.

All articles identified in the database search were exported to Zotero 5.0.66 (http://www.zotero.org) and any duplicates were deleted. Two reviewers (Y.K. and M.V.) initially screened, included, and excluded studies based on titles and abstracts. Full text of identified articles was obtained and reviewed by the first and second reviewers (Y.K. and M.V.). Disagreements were resolved by discussion and third (E.B.) and fourth (B.W.) reviewers were consulted as necessary. This systematic review and meta-analysis was prospectively registered in the Open Science Framework (OSF). The OSF registration number was 9bc4y. Protocol details can be accessed via https://osf.io/9bc4y.

Eligibility criteria

Type of participants

Studies that recruited adults aged 65 years or older were included. There was no restriction on the injury or disorder type, settings, and the history of falls. Animal studies and human studies with participants aged under 65 were excluded.

Type of studies

Studies conducted as a randomized control trial (RCT) and published in the English language were considered for inclusion. Studies with other research designs or non-peer-reviewed articles were excluded.

Intervention

Studies that employed all types of AE with a description of intervention details, such as duration, frequency, type, and intensity of AE, were included. The studies must have included a minimum of one AE group and a comparison group participating in another exercise program on dry land. Studies that did not include exercise components, such as bath or spa therapies, were excluded.

Outcome measures

Studies must have reported at least one outcome related to dynamic balance and compared the outcomes between AE and LE groups. All outcome measures must have been conducted on land because postural adjustment and movement patterns are significantly altered in water (T. Louder et al., 2014; T. J. Louder et al., 2019; Silvers et al., 2014), and daily living activities are mostly performed on dry land. Studies including mixed intervention (e.g., both AE and LE in all groups) were excluded and any studies not providing data on the baseline or end-point outcomes were additionally excluded from the meta-analysis.

Data extraction and coding

A total of 11 studies meeting the eligibility criteria were reviewed and coded in REDCap (https://www.project-redcap.org/). All relevant information was extracted for each study as follows: (1) report characteristics (2) participants (3) AE settings (4) interventions (5) outcome measures (6) results. The included studies were assessed and coded independently by two reviewers (Y.K. and M.V.) and discussed for consensus. If there was a disagreement, the study was re-evaluated to achieve consensus.

Risk of bias and publication bias assessment

The analysis of the methodological quality and risk of bias of the included studies was conducted using the Cochrane risk of bias tool (RoB 2) (Sterne et al., 2019) independently by two authors (Y.K. and M.V.). The tool can be utilized to assess the impact of each potential source of bias, at the "low", "high", and "somewhat concerns" risk level, respectively. The following criteria that potentially affect the risk of bias were addressed: randomization process, deviation from intended interventions, missing outcome data, measurement of outcome, selection of the reported result, and overall bias. Any disagreements were discussed until consensus was reached and additionally arbitrated by the third (E.B.) and fourth (B.W.) reviewers if needed. "Small study effects" is a generic term for the phenomenon that smaller studies sometimes show different, often larger, treatment effects than large studies (Sterne et al., 2000). In meta-analyses, small study effects are a well-known challenging and critical issue that may threaten the validity of the study results, and the most well-known reason for the small study effects is publication bias (Sterne et al., 2000). The publication bias can be displayed graphically in funnel plots, thus, a small study effect was examined and interpreted through a test for funnel plot asymmetry (Sterne et al., 2011). In the absence of publication bias, the plot should be shaped like a symmetrical funnel with small studies scattered widely at the bottom of the graph and larger studies spread narrowly (Sterne et al., 2000).

Meta-analysis

The purpose of the meta-analyses was to compare the pooled effect size between the AE group and LE group on dynamic balance in older adults. For the post-intervention sample size, when all subjects at the baseline were followed up, assessed, and analyzed regardless of their compliance to the intervention (intention-to-treat), the data including means and standard deviations for each outcome measure were used on the preferential basis ("ICH Harmonised Tripartite Guideline. Statistical Principles for Clinical Trials. International Conference on Harmonisation E9 Expert Working Group," 1999). Otherwise, the data of subjects who completed a pre-determined intervention(s) and have measurable data at the primary end point without any major protocol violations (per protocol) were used ("ICH Harmonised Tripartite Guideline. Statistical Principles for Clinical Trials. International Conference on Harmonisation E9 Expert Working Group," 1999). When data were not reported in the article as means and standard deviations, we contacted the corresponding authors and requested the data.

Outcome measurements included in the meta-analysis were assigned into three categories: (a) dynamic steady-state balance (e.g., 5-m walk test, 10-m walk test, backward tandem walk), (b) proactive balance (e.g., FRT; Functional Reach Test, TUG; Timed Up and Go test, 8-foot up-and-go test), and (c) balance test batteries (e.g., BBS; Balance Berg Scale and BOOMER; Balance Outcome Measure for Elder Rehabilitation) (Shumway-Cook & Woollacott, 2017). Where a trial reported more than one outcome in one of these categories, only one outcome with the highest priority was used for the analysis in line with Lesinski et al. (Lesinski et al., 2015). The highest priority was given to the gait speed in the dynamic steady-state balance, FRT in the proactive balance, and BBS in the balance test battery (Lesinski et al., 2015). When these representative outcomes were not available, the most similar outcomes related to the temporal (duration) and spatial (form of the motion) structure were used (Lesinski et al., 2015). For a crossover RCT study (Adsett et al., 2017), first-phase data were used. Sensitivity analyses were additionally performed to explore the robustness of the results by quantifying the differences in outcomes when removing one trial with a distinctly different direction of change in each category of balance outcome measurements.

The effect sizes between AE and LE groups were described as standardized mean differences (SMD) and 95% confidence intervals (CI). An effect size (SMD) 0.2-0.5, 0.5-0.8, and >0.8 were considered a small, moderate, and large effect, respectively (Cohen, 1988). In case of a lower score indicating better performance in dynamic balance, scale directions were adjusted by multiplying -1 to data, which resulted in a positive value indicating an improvement in favor of AE. For all analyses, we used an inverse-variance weighted random-effects model. All meta-analyses were performed using the Cochrane Collaboration's Review Manager Software (RevMan 5.3.).

Results

Study selection

The electronic search retrieved a total of 2969 potential studies in the five databases, and no additional studies were identified by hand searching. Of these studies, 1491 duplicates were removed, and 1445 studies were excluded based on title and abstract content. We obtained the full text of the remaining 33 trials, 22 of which were excluded because they did not meet eligibility criteria. Finally, 11 studies were retained for our systematic review, and 10 studies were included in the meta-analysis after excluding one study due to insufficient data (Avelar et al., 2010). The flow diagram in Figure 2-1 schematizes the steps of the selection of the studies.

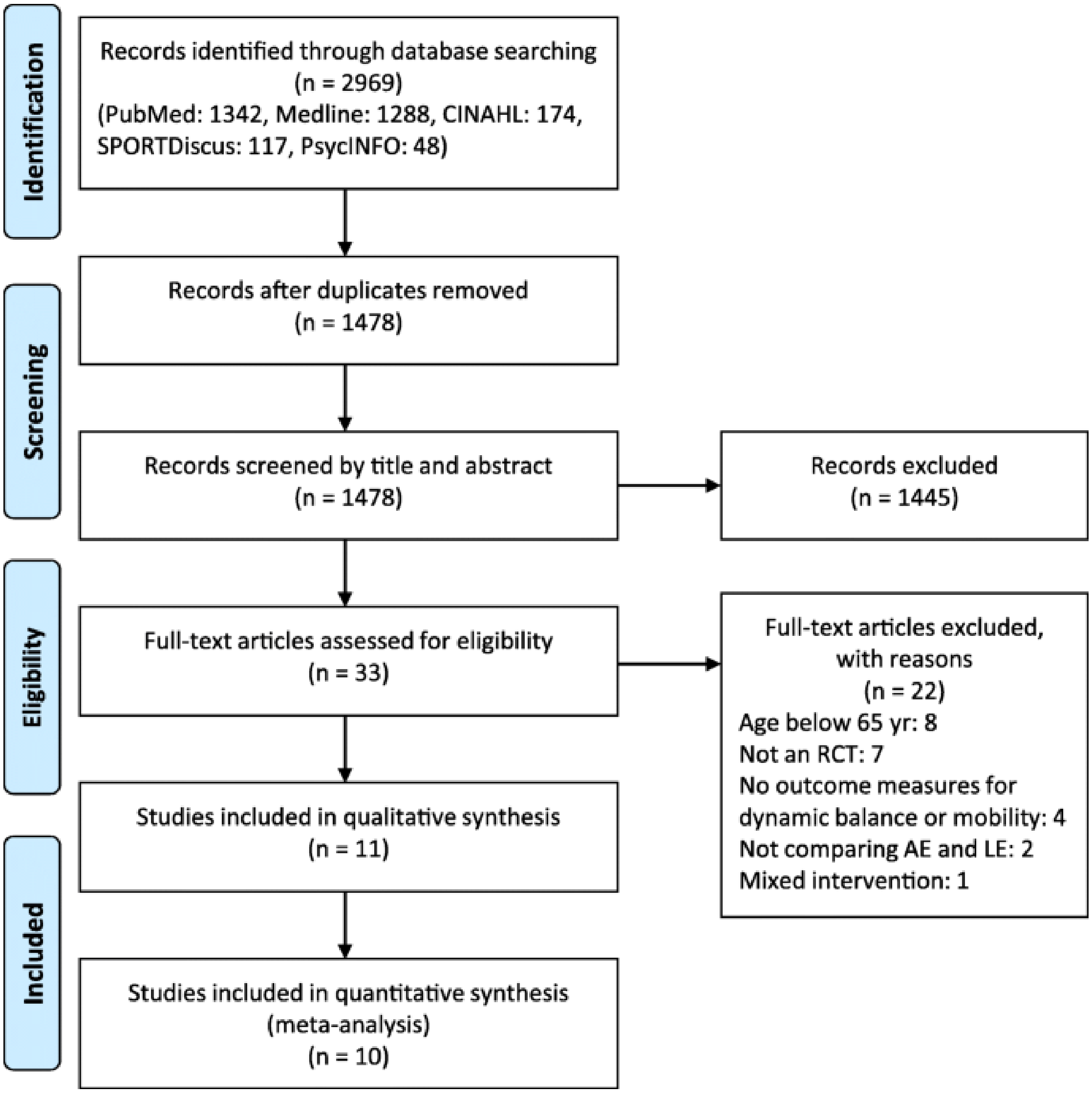


Figure 2-1. PRISMA flow diagram of article selection process.

Characteristics of included studies

Participants

Eleven studies included in this systematic review were randomized controlled trials, which compared the impacts of AE and LE on dynamic balance in older adults aged 65 years or older. Table 2-1 presents the characteristics of participants of the 11 eligible studies that provided data for 372 participants with the mean age of 69.6 ± 4.0 years. The participants were recruited from the community (Arnold et al., 2008; Avelar et al., 2010; Simmons & Hansen, 1996), hospital (Adsett et al., 2017; Bergamin et al., 2013; Zivi et al., 2018), and Parkinson’s associations (Pérez de la Cruz, 2017; Pérez-de la Cruz, 2018; Vivas et al., 2011). Attrition rates were calculated using the following formula: Number of participants lost at post-intervention/number of participants at baseline*100. The attrition rates ranged from 0% to 27%.

Table 2-1

Characteristics of participants and exercise environments

Study	Group	Sample size (post-intervention)	Drop-outs (attrition rate: %)	Age: mean (SD)	Diagnosis	Type of pool/Gym	Water depth	Water/Room temperature (°C)
Adsett et al 2017	AE	36 (33)	3 (8%)	72.9 (8.4)	Heart failure	Heated pool in hospital	Chest level	33-34
	LE	25 (25)	0 (0%)	68.3 (11.3)		Gymnasium in the hospital	NA	NR
Arnold et al 2008	AE	21 (16)	5 (24%)	68.6 (5.4)	Osteoporosis	Community pool	Varied from shoulder to waist	30
	LE	20 (15)	5 (25%)	69.1 (6.3)		Community gym	NA	NR
Avelar et al 2010	AE	14 (12)	2 (14%)	68.0 (5.7)	Healthy	Physical therapy pool	NR	NR
	LE	15 (14)	1 (7%)	69.0 (5.6)		Physical therapy gym	NA	NR
Bergamin et al 2013	AE	20 (17)	3 (15%)	Total: 71.2 (5.4)	Healthy	Hot spring water	1.3-1.8 m	36.2
	LE	20 (17)	3 (15%)			NR	NA	20.1
Pérez de la Cruz et al 2017	AE	15 (15)	0 (0%)	66.8 (5.3)	Parkinson's	Indoor pool	1.1-1.45 m	30 (room: 27.5)
	LE	15 (15)	0 (0%)	67.5 (9.9)		Gym (varied)	NA	NR
Pérez de la Cruz et	AE	14 (14)	0 (0%)	65.9 (7.1)	Parkinson’s	Indoor pool	1.1m	30 (room: 27.5)

al 2018	LE	15 (15)	0 (0%)	66.4 (5.7)		NR	NA	NR
Simmons and Hansen 1996	AE	13 (10)	3 (23%)	82.0 (5.4)	Healthy	Outdoor pool	1-1.4 m (between waist and nipple line)	29.4-32.2
	LE	13 (12)	1 (8%)	78.2 (5.8)		Carpeted indoor church hall	NA	NR
Vivas et al 2011	AE	6 (5)	1 (17%)	65.7 (3.7)	Parkinson's	City spa	1.3 m	32
	LE	6 (6)	0 (0%)	68.3 (6.9)		NR	NA	NR
Volpe et al2014	AE	17 (17)	0 (0%)	68.0 (7.0)	Parkinson's	NR	NR	NR
	LE	17 (17)	0 (0%)	66.0 (8.0)		NR	NA	NR
Volpe et al 2017	AE	15 (13)	2 (13%)	70.6 (7.8)	Parkinson's	Therapeutic swimming pool	Chest level (Mammillary line)	NR
	LE	15 (11)	4 (27%)	70.0 (7.8)		NR	NA	NR
Zivi et al., 2018	AE	21 (21)	0 (0%)	66.3 (13.0)	Peripheral neuropathies	Heated swimming pool	NR	32
	LE	19 (19)	0 (0%)	71.8 (7.7)		NR	NA	NR

AE aquatic exercise, *LE* land exercise, *NR* not reported, *NA* not available.

Aquatic setting and interventions

First, focusing on the pool characteristics, 10 studies reported the type of pool where the AE took place: Five at indoor swimming pools, three at therapeutic pools, two at outdoor swimming pools, and one not reported. The water depth varied from 1 m to 1.8 m, and the water temperature ranged between 27.5°C and 36.2°C (31.5±2.6°C) with an exception of three studies not reporting the aquatic setting (Avelar et al., 2010; Volpe et al., 2014, 2017). The characteristics of pools are reported in Table 2-1.

The AE programs exhibited substantial differences across all included studies in regards to the intervention duration (45-60 min), frequency (1-5 sessions per week), and total duration (4-20 weeks) (Table 2-2). The AE programs identified included gait, mobility, stretching, stabilization, resistance, balance, endurance, strengthening, aerobic training, and Ai Chi. The exercises provided for AE and LE groups had the same or similar types, volume, emphasis, and objectives, except for two studies (Pérez de la Cruz, 2017; Pérez-de la Cruz, 2018). Table 2-2 presents a summary of the exercise programs.

Table 2-2

Summary of exercise program

Study	Administrator	Dosage		Total duration (week)		Warm-up (min)	Main exercise (min)	Cool down (min)	Exercise details	Individually adjusted intensity	Aids/ equipment for AE
		Min/ session	Time/ week								
Adsett et al 2017	Physical therapist	60	1	6		Yes (time NR)	45	Yes (time NR)	Upper and lower limb endurance and resistance exercises	Y (RPE)	Cycling, steps, hand paddles, floatation rings
Arnold et al 2008	Physical therapist	50	3	20		15	30	5	Gait, postural correction, upper/lower extremity mobility and stretching, trunk stabilization, resistance exercises, balance	Y (RPE)	Music, paddleboards, small weights, flotation devices
Avelar et al 2010	NR	NR	2	6		3.5	NR (reps: 4x20)	3	Endurance exercises	NR	NR
Bergamin et al 2013	Exercise trainer	60	2	6		8	50	8	Lower and upper body exercises (joint mobility, strengthening)	Y (RPE)	Not used
Pérez de la Cruz et al 2017	Physical therapist	45	2	10	AE	Yes (time NR)	35	Yes (time NR)	Aquatic Ai Chi	NR	NR
					LE	10	25	10	Strength and aerobic exercises		
Pérez de la Cruz et al 2018	Physical therapist	45	2	11	AE	Yes (time NR)	30	Yes (time NR)	Aquatic Ai Chi	NR	NR
					LE	10	30-40	20	Strength and aerobic exercises		
Simmons and Hansen 1996	NR	45	2	5		NR	45	NR	Gait training	NR	NR
Vivas et al 2011	Physical therapist	45	2	4		10	35	0	Trunk mobility, postural stability training, dynamic balance	Y	Flotation devices, water turbulence, balance plate, stick and hoop
Volpe et al 2014	NR	60	5	8		10	40	10	Perturbation-based balance training	NR	NR
Volpe et al 2017	Physical therapist	60	5	8		10	40	10	Exercises for postural deformities	NR	Flotation device
Zivi et al., 2018	Physical therapist	60	3	4		NR	60	NR	Balance, posture control, and gait exercises	NR	Treadmill, cycloergometer, cyclette, stabilometric platform

AE aquatic exercise, *LE* land exercise, *NR* not reported, *RPE* the Borg rating of perceived exertion scale

Outcome measurements and summary of the results

All studies included in this review performed at least one dynamic balance-related measurement before and after the intervention on land. Four studies evaluated long-term effects at additional stages after the intervention was terminated (Pérez de la Cruz, 2017; Pérez-de la Cruz, 2018; Vivas et al., 2011; Volpe et al., 2017), but the second post-intervention outcome measure data were not used due to differences in the time points after interventions and limited data. Overall, eight studies reported greater improvements in AE groups compared to LE groups in at least one dynamic balance outcome measurement (Arnold et al., 2008; Bergamin et al., 2013; Pérez de la Cruz, 2017; Pérez-de la Cruz, 2018; Simmons & Hansen, 1996; Vivas et al., 2011; Volpe et al., 2014; Zivi et al., 2018), whereas two studies did not find any statistically significant differences between AE and LE groups (Avelar et al., 2010; Volpe et al., 2017), and one study reported a greater improvement in LE group in one outcome measurement (Adsett et al., 2017). Table 2-3 presents the details of outcome measurements and a brief summary of the results of individual studies.

Table 2-3

Outcome measures and summary of main findings of all selected studies

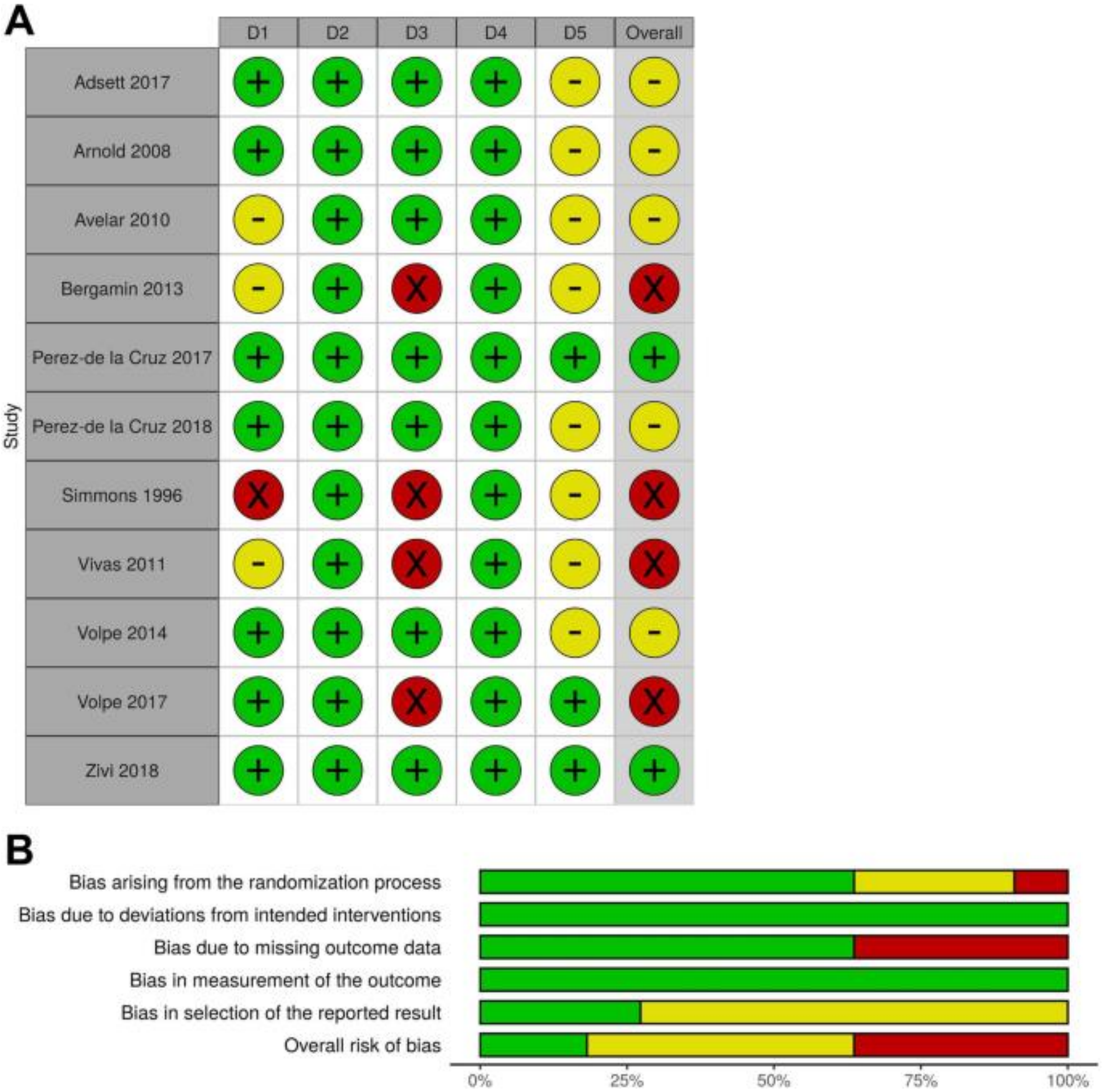
Study	Outcome measures	Follow-up	Adverse events	Participants feedback	Results
Adsett et al 2017	6MWT, **TUG**, **10-m walk test (speed)**, **BOOMER**	N	Shortness of breath (1), dizziness (2)	Reported	LE group showed greater improvements in 6MWT. No significant differences in 10-m gait speed and BOOMER.
Arnold et al 2008	**BBS**, **FRT**, **backward tandem walk**	N	Pain: 29% AE, 52% LE. Muscle cramping and stiffness: 25% AE, 3% LE	NR	AE group showed a greater improvement only in the backward tandem walk versus LE group. No significant differences in BBS and FRT between the two groups.

Avelar et al 2010	DGI, BBS, Tandem gait test, 10-m gait speed test	N	NR	NR	Both intervention groups showed improvements only in DGI and BBS, with no difference between groups.
Bergamin et al 2013	**8-foot up-and-go test**	N	None	NR	Both intervention groups showed improvements, with significantly greater improvement in AE group.
Pérez de la Cruz et al 2017	**BBS**, Tinetti Scale, FTSTS, **TUG**	1 month	None	NR	Only AE group showed improvements in all variables, except the FTSTS. LE group showed no improvements in any of the balance measures.
Pérez de la Cruz et al 2018	**TUG**, FTSTS,	1 month	NR	NR	AE (Ai Chi) group showed improvements in TUG and FTSTS in post-treatment and 1-month follow-up, whereas the dryland group showed no significant differences.
Simmons and Hansen 1996	**FRT**	N (10-12: injury tracking)	NR	NR	AE group showed gradual improvements in each week. LE group showed improvement only in the initial week. At week 5 (post), AE group showed significant improvement compared to LE groups.
Vivas et al 2011	**FRT**, **BBS**, **5-m walk test**, TUG	17 days	NR	NR	Both exercise groups showed improvements in FRT. Only the AE group improved in the BBS.
Volpe et al2014	**Instrumental version of FRT**, TUG, **BBS**,	N	None	NR	Both groups showed improvements in all outcome variables, with a better improvement in AE group BBS.
Volpe et al 2017	**TUG**, **BBS**,	2 months	NR	NR	Both groups showed improvements in all parameters, with no intergroup differences.
Zivi et al., 2018	**BBS**, Dynamic Gait Index	N	NR	NR	AE group showed a greater improvement in the Dynamic Gait Index. No significant difference in BBS between groups.

Outcome measurements included in the meta-analysis were highlighted (bold), *AE* aquatic exercise, *LE* land exercise, *NR* not reported, *DGI* Dynamic gait index, *BBS* Berg Balance Scale, *FTSTS* Five Times Sit-to-Stand test, *TUG* Timed Up and Go test, *FRT* Functional Research Test, *6MWT* 6-minute walk test, *BOOMER* Balance Outcome Measure for Elder Rehabilitation

Risk of bias and publication bias

The Cochrane risk of bias tool indicated a “low” risk of bias for two studies (Pérez de la Cruz, 2017; Zivi et al., 2018) and “high” risk of bias for four studies (Bergamin et al., 2013; Simmons & Hansen, 1996; Vivas et al., 2011; Volpe et al., 2017) due to randomization process (Simmons & Hansen, 1996) and missing outcome data (Bergamin et al., 2013; Simmons & Hansen, 1996; Vivas et al., 2011; Volpe et al., 2017). The other five studies had "somewhat concerns" (Adsett et al., 2017; Arnold et al., 2008; Avelar et al., 2010; Pérez-de la Cruz, 2018; Volpe et al., 2014) due to the randomization process (Avelar et al., 2010) and selection of the reported result (Adsett et al., 2017; Arnold et al., 2008; Avelar et al., 2010; Pérez-de la Cruz, 2018; Volpe et al., 2014). Figure 2-2 presents the risk of bias of the included studies. The visual inspection of the funnel plot identified substantial asymmetry, indicating the possibility of publication bias in the meta-analysis (figure 2-3).



Study	D1	D2	D3	D4	D5	Overall
Adsett 2017	+	+	+	+	-	-
Arnold 2008	+	+	+	+	-	-
Avelar 2010	-	+	+	+	-	-
Bergamin 2013	-	+	X	+	-	X
Perez-de la Cruz 2017	+	+	+	+	+	+
Perez-de la Cruz 2018	+	+	+	+	-	-
Simmons 1996	X	+	X	+	-	X
Vivas 2011	-	+	X	+	-	X
Volpe 2014	+	+	+	+	-	-
Volpe 2017	+	+	X	+	+	X
Zivi 2018	+	+	+	+	+	+

Figure 2-2. Risk of bias of the included studies. (A) Risk of bias graph, (B) Risk of bias summary. Green, low risk; yellow, somewhat concerns; red, high risk. D1, Randomization process; D2, Deviation from intended interventions; D3, missing outcome data; D4, measurement of outcome; D5, selection of the reported result; Overall, overall bias.

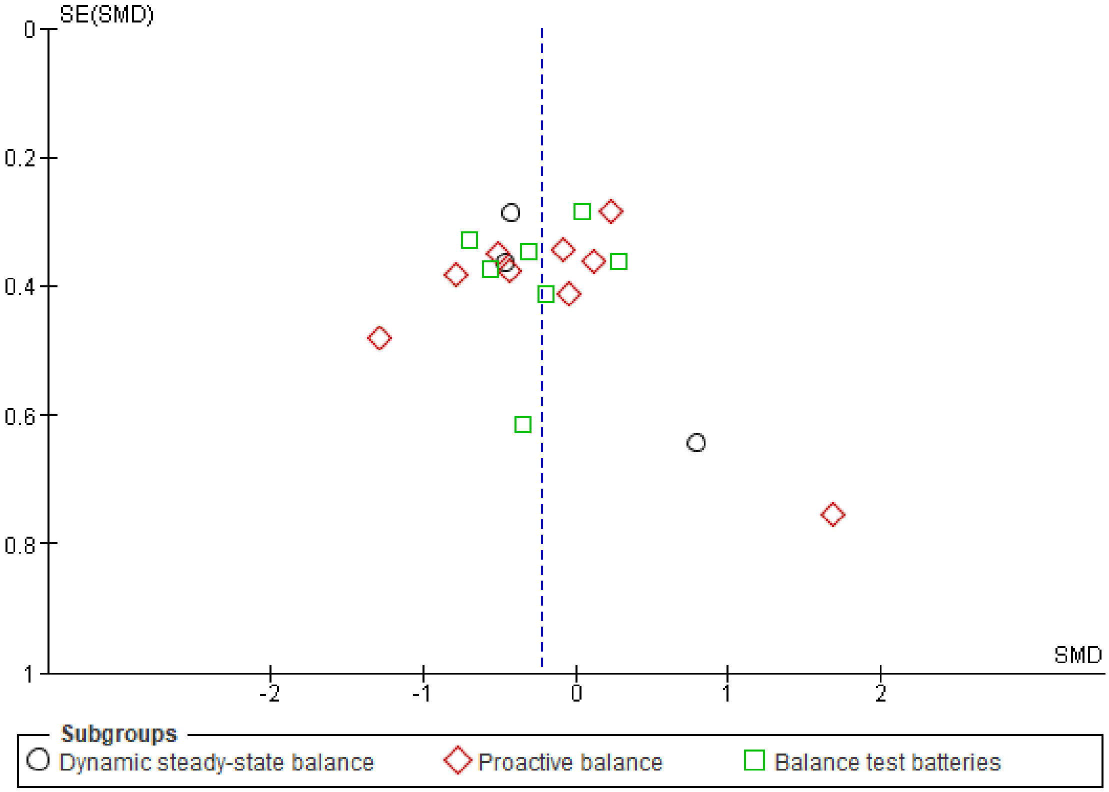
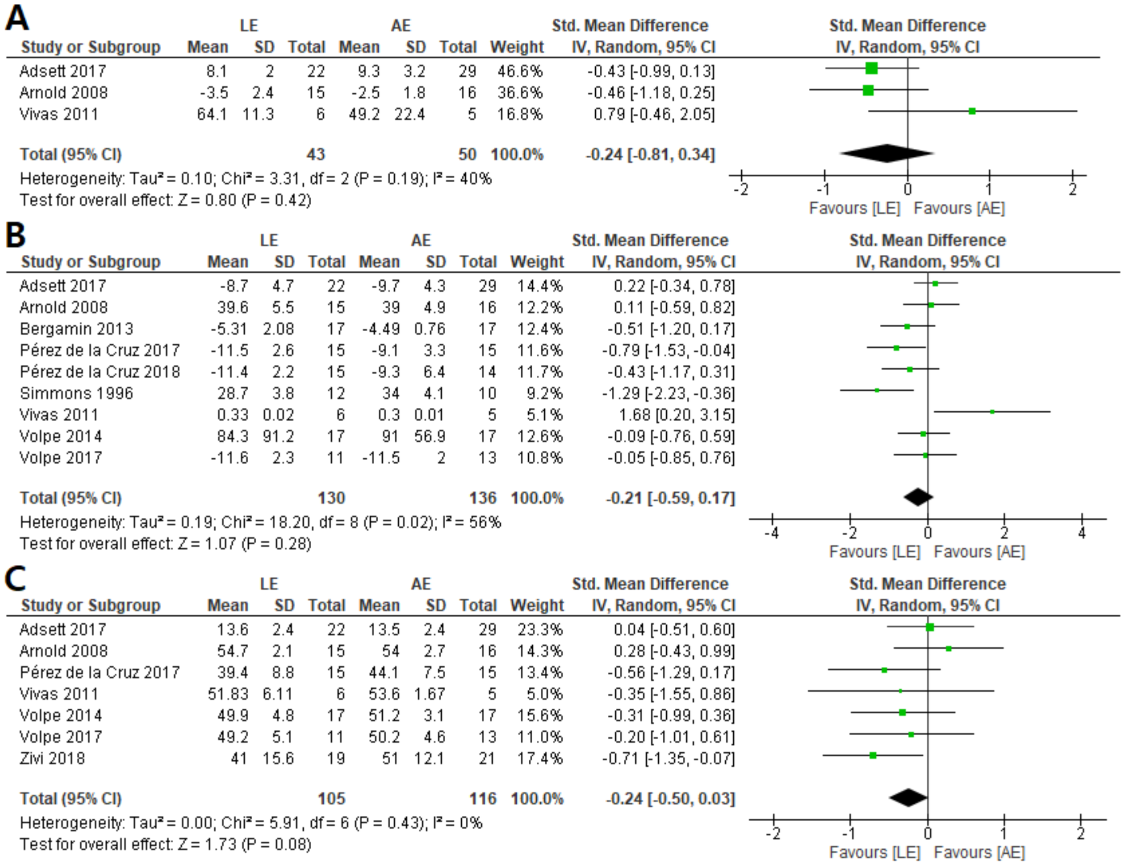


Figure 2-3. Funnel plot for all of the meta-analyses.

Meta-analysis

Post-intervention assessment data for BBS, Dynamic Gait Index, tandem gait, and 10m gait speed from the study by Avelar et al. (Avelar et al., 2010), data for 5-m walk test, FRT, and TUG from the study by Vivas et al. (Vivas et al., 2011), data for BBS from the study by Arnold et al. (Arnold et al., 2008), and data for 10-m gait speed and BOOMER from the study by Adsett et al. (Adsett et al., 2017) were requested, and all data, except those from the study by Avelar et al., were received. Thus, a total of 10 studies were included in the meta-analysis of dynamic balance outcomes for AE compared with LE (Adsett et al., 2017; Arnold et al., 2008; Bergamin et al., 2013; Pérez de la Cruz, 2017; Pérez-de la Cruz, 2018; Simmons & Hansen, 1996; Vivas et al., 2011; Volpe et al., 2014, 2017; Zivi et al., 2018).

Outcome measurements included in each category were as follows: (a) dynamic steady-state balance: 10-m walk test (speed) (Adsett et al., 2017), 5-m walk test (speed) (Vivas et al., 2011), and backward tandem walk (number of errors) (Arnold et al., 2008), (b) proactive balance: FRT (Arnold et al., 2008; Simmons & Hansen, 1996; Vivas et al., 2011; Volpe et al., 2014), TUG (Adsett et al., 2017; Pérez de la Cruz, 2017; Pérez-de la Cruz, 2018; Volpe et al., 2017), and 8-foot up-and-go test (Bergamin et al., 2013), (c) balance test batteries: BBS (Arnold et al., 2008; Pérez de la Cruz, 2017; Vivas et al., 2011; Volpe et al., 2014, 2017; Zivi et al., 2018) and BOOMER (Adsett et al., 2017). When a random-effect analysis was applied using the 10 studies involving 343 participants, AE groups compared with LE groups displayed comparable improvements in dynamic steady-state balance (SMD = -0.24; 95% CI, -.81 to .34), proactive balance (SMD = -0.21; 95% CI, -.59 to .17), and balance test batteries (SMD = -0.24; 95% CI, -.50 to .03) (Figure 2-4). The sensitivity analyses after excluding one trial with a distinctly opposite direction of change in each category presented that the point estimates changed by -0.20 (SMD = -0.44; 95% CI, -.88 to 0) in dynamic steady-state balance, by -0.08 (SMD = -0.29; 95% CI, -62 to .03) in proactive balance, and by -0.08 (SMD = -0.32; 95% CI, -.61 to -.03) in balance test batteries (Figure 2-5).



A

Study or Subgroup	LE Mean	LE SD	LE Total	AE Mean	AE SD	AE Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adsett 2017	8.1	2	22	9.3	3.2	29	46.6%	-0.43 [-0.99, 0.13]
Arnold 2008	-3.5	2.4	15	-2.5	1.8	16	36.6%	-0.46 [-1.18, 0.25]
Vivas 2011	64.1	11.3	6	49.2	22.4	5	16.8%	0.79 [-0.46, 2.05]
Total (95% CI)			**43**			**50**	**100.0%**	**-0.24 [-0.81, 0.34]**

Heterogeneity: Tau² = 0.10; Chi² = 3.31, df = 2 (P = 0.19); I² = 40%
Test for overall effect: Z = 0.80 (P = 0.42)

B

Study or Subgroup	LE Mean	LE SD	LE Total	AE Mean	AE SD	AE Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adsett 2017	-8.7	4.7	22	-9.7	4.3	29	14.4%	0.22 [-0.34, 0.78]
Arnold 2008	39.6	5.5	15	39	4.9	16	12.2%	0.11 [-0.59, 0.82]
Bergamin 2013	-5.31	2.08	17	-4.49	0.76	17	12.4%	-0.51 [-1.20, 0.17]
Pérez de la Cruz 2017	-11.5	2.6	15	-9.1	3.3	15	11.6%	-0.79 [-1.53, -0.04]
Pérez de la Cruz 2018	-11.4	2.2	15	-9.3	6.4	14	11.7%	-0.43 [-1.17, 0.31]
Simmons 1996	28.7	3.8	12	34	4.1	10	9.2%	-1.29 [-2.23, -0.36]
Vivas 2011	0.33	0.02	6	0.3	0.01	5	5.1%	1.68 [0.20, 3.15]
Volpe 2014	84.3	91.2	17	91	56.9	17	12.6%	-0.09 [-0.76, 0.59]
Volpe 2017	-11.6	2.3	11	-11.5	2	13	10.8%	-0.05 [-0.85, 0.76]
Total (95% CI)			**130**			**136**	**100.0%**	**-0.21 [-0.59, 0.17]**

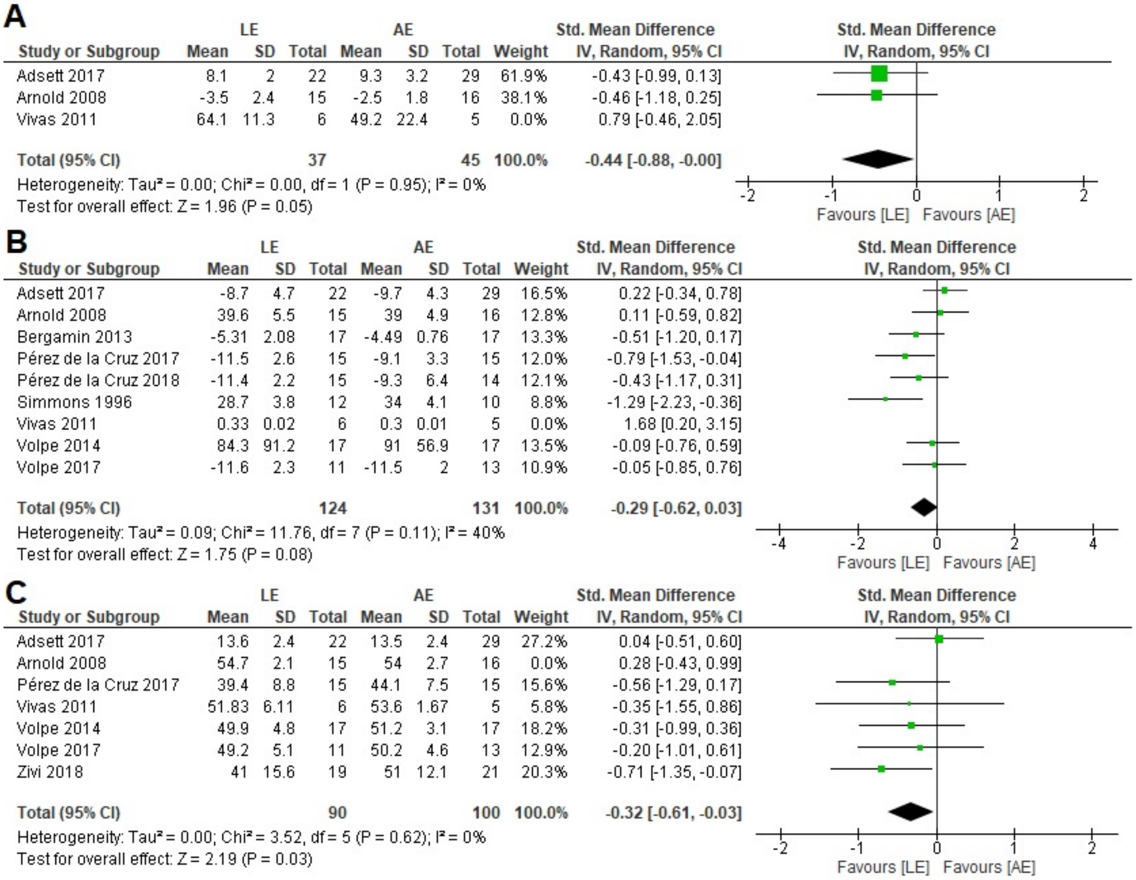
Heterogeneity: Tau² = 0.19; Chi² = 18.20, df = 8 (P = 0.02); I² = 56%
Test for overall effect: Z = 1.07 (P = 0.28)

C

Study or Subgroup	LE Mean	LE SD	LE Total	AE Mean	AE SD	AE Total	Weight	Std. Mean Difference IV, Random, 95% CI
Adsett 2017	13.6	2.4	22	13.5	2.4	29	23.3%	0.04 [-0.51, 0.60]
Arnold 2008	54.7	2.1	15	54	2.7	16	14.3%	0.28 [-0.43, 0.99]
Pérez de la Cruz 2017	39.4	8.8	15	44.1	7.5	15	13.4%	-0.56 [-1.29, 0.17]
Vivas 2011	51.83	6.11	6	53.6	1.67	5	5.0%	-0.35 [-1.55, 0.86]
Volpe 2014	49.9	4.8	17	51.2	3.1	17	15.6%	-0.31 [-0.99, 0.36]
Volpe 2017	49.2	5.1	11	50.2	4.6	13	11.0%	-0.20 [-1.01, 0.61]
Zivi 2018	41	15.6	19	51	12.1	21	17.4%	-0.71 [-1.35, -0.07]
Total (95% CI)			**105**			**116**	**100.0%**	**-0.24 [-0.50, 0.03]**

Heterogeneity: Tau² = 0.00; Chi² = 5.91, df = 6 (P = 0.43); I² = 0%
Test for overall effect: Z = 1.73 (P = 0.08)

Figure 2-4. Forest plot of comparison: AE versus LE. (A) Dynamic steady-state balance, (B) Proactive balance, (C) Balance test batteries.



A

	LE			AE				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Adsett 2017	8.1	2	22	9.3	3.2	29	61.9%	-0.43 [-0.99, 0.13]
Arnold 2008	-3.5	2.4	15	-2.5	1.8	16	38.1%	-0.46 [-1.18, 0.25]
Vivas 2011	64.1	11.3	6	49.2	22.4	5	0.0%	0.79 [-0.46, 2.05]
Total (95% CI)			**37**			**45**	**100.0%**	**-0.44 [-0.88, -0.00]**

Heterogeneity: Tau² = 0.00; Chi² = 0.00, df = 1 (P = 0.95); I² = 0%
Test for overall effect: Z = 1.96 (P = 0.05)

B

	LE			AE				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Adsett 2017	-8.7	4.7	22	-9.7	4.3	29	16.5%	0.22 [-0.34, 0.78]
Arnold 2008	39.6	5.5	15	39	4.9	16	12.8%	0.11 [-0.59, 0.82]
Bergamin 2013	-5.31	2.08	17	-4.49	0.76	17	13.3%	-0.51 [-1.20, 0.17]
Pérez de la Cruz 2017	-11.5	2.6	15	-9.1	3.3	15	12.0%	-0.79 [-1.53, -0.04]
Pérez de la Cruz 2018	-11.4	2.2	15	-9.3	6.4	14	12.1%	-0.43 [-1.17, 0.31]
Simmons 1996	28.7	3.8	12	34	4.1	10	8.8%	-1.29 [-2.23, -0.36]
Vivas 2011	0.33	0.02	6	0.3	0.01	5	0.0%	1.68 [0.20, 3.15]
Volpe 2014	84.3	91.2	17	91	56.9	17	13.5%	-0.09 [-0.76, 0.59]
Volpe 2017	-11.6	2.3	11	-11.5	2	13	10.9%	-0.05 [-0.85, 0.76]
Total (95% CI)			**124**			**131**	**100.0%**	**-0.29 [-0.62, 0.03]**

Heterogeneity: Tau² = 0.09; Chi² = 11.76, df = 7 (P = 0.11); I² = 40%
Test for overall effect: Z = 1.75 (P = 0.08)

C

	LE			AE				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Adsett 2017	13.6	2.4	22	13.5	2.4	29	27.2%	0.04 [-0.51, 0.60]
Arnold 2008	54.7	2.1	15	54	2.7	16	0.0%	0.28 [-0.43, 0.99]
Pérez de la Cruz 2017	39.4	8.8	15	44.1	7.5	15	15.6%	-0.56 [-1.29, 0.17]
Vivas 2011	51.83	6.11	6	53.6	1.67	5	5.8%	-0.35 [-1.55, 0.86]
Volpe 2014	49.9	4.8	17	51.2	3.1	17	18.2%	-0.31 [-0.99, 0.36]
Volpe 2017	49.2	5.1	11	50.2	4.6	13	12.9%	-0.20 [-1.01, 0.61]
Zivi 2018	41	15.6	19	51	12.1	21	20.3%	-0.71 [-1.35, -0.07]
Total (95% CI)			**90**			**100**	**100.0%**	**-0.32 [-0.61, -0.03]**

Heterogeneity: Tau² = 0.00; Chi² = 3.52, df = 5 (P = 0.62); I² = 0%
Test for overall effect: Z = 2.19 (P = 0.03)

Figure 2-5. Results of sensitivity analyses. (A) Dynamic steady-state balance, (B) Proactive balance, (C) Balance test batteries.

Discussion

This is the first systematic review with a meta-analysis comparing the effects of AE and LE on dynamic balance in older adults. Eight of the included studies (Arnold et al., 2008; Bergamin et al., 2013; Pérez de la Cruz, 2017; Pérez-de la Cruz, 2018; Simmons & Hansen, 1996; Vivas et al., 2011; Volpe et al., 2014; Zivi et al., 2018) concluded that AE resulted in greater improvements in at least one dynamic balance outcome measurement compared to LE, and one study (Adsett et al., 2017) reported LE led to greater improvements in one dynamic balance outcome than AE. However, the results of the meta-analysis revealed no statistically significant differences in all outcome categories. This result is consistent with a previous review conducted by Waller et al. (2016) that compared the effects of aquatic and land-based exercise programs on physical functioning in healthy older adults and demonstrated small effect sizes in postural stability in favor of AE and in walking ability in favor of LE (Waller et al., 2016). In consideration of the limited number of studies included in this analysis and results of the sensitivity analyses, however, the results must be interpreted with caution.

Although different musculoskeletal or neurological disorders do not share identical signs or symptoms, dynamic balance is important across all older populations to prevent fall risk and to enhance rehabilitation from fall-related injuries. For example, Parkinson’s disease is a degenerative neurological disorder commonly reported in the senior population, and the risk of falls and fall-related injuries increase in this population due to deficits in motor functions and postural stability (Conway et al., 2018). Osteoporosis, which is also common in the senior population, reduces bone density and results in a higher risk of fractures caused by falling (Cauley, 2017). In addition, those with osteoporosis commonly show muscle weakness, postural deformity, and deteriorated postural control that may significantly increase the risk of falls and fractures (Abreu et al., 2010; Liu-Ambrose et al., 2003). Thus, various balance abilities have to be trained from both preventive and rehabilitative perspectives in those populations. Moreover, dynamic balance is a common interest in all senior populations regardless of the disorder because aging brings a natural biological degeneration in regards to muscle strength and mass and neurological functions (Granacher et al., 2011). Thus, older adults without any disorder also present a greater risk of falls when compared to younger adults due to inappropriate muscular activation and control of the body’s center of mass during ambulation (e.g., dynamic balance) (Bosse et al., 2012). The comparably effective AE and LE in overall older adults suggests that participants can select the training environment based on their preference.

Intervention and outcomes

Postural strategies vary in different environments regardless of age and physical fitness (Bressel, Louder, & Dolny, 2017). Both older and younger adult populations demonstrated the greatest postural sway and sway velocity with the lowest perceived stability in chest-deep water compared to the same measures made at shallow water depths and on land (Bressel, Louder, & Dolny, 2017; T. Louder et al., 2014; Schaefer et al., 2016). However, none of the trials included in this current review provided a rationale for the water depth chosen and considered each participant’s height. Although all studies recruited both male and female participants with different mean heights, except for only one trial by Arnold et al. (2008), the AEs were conducted in water with the non-adjustable water level. That implies the participants in the AE groups were trained with all different exercise intensities despite the identical location, settings, and exercise types. In addition, movement patterns and mechanical power outputs during the same physical performance are presented differently in water and on land (T. Louder et al., 2018). Thus, although most of the trials included provided the same or similar exercise programs to both AE and LE groups, the subjective exercise intensities can be different due to the environmental factors, which may affect the ultimate training effects. The main reason AE is recommended to the older adults is to utilize the physical properties of water and provide an optimized medium for exercise. Therefore, it is recommended that future studies provide rationales for water depth and exercise intensities in all intervention groups to investigate and compare the effects between AE and LE more accurately.

The intervention dose, duration, intensity, and type of exercise varied considerably in each trial, but there was no justification for the exercise dose chosen. According to ‘The 2018 Department of Health and Human Services’ guideline (US Department of Health and Human Services, 2018), older adults should get at least 150 minutes per week of moderate-intensity or 75 minutes per week of vigorous-intensity aerobic activity with moderate or high-intensity muscle-strengthening activities at least 2 days a week. Specifically, it is recommended for older adults with the risk of falls to participate in balance training three or more times per week to reduce falls. Older adults in three trials participated in AE and LE at least 150 minutes per week (Arnold et al., 2008; Volpe et al., 2014, 2017), and those in two trials practiced balance training at least 3 times per week (Arnold et al., 2008; Volpe et al., 2014). The intensity of the activities can be perceived in different ways according to various factors, such as physical fitness, muscular performance, or level of disorder or degeneration. Only two studies (Arnold et al., 2008; Bergamin et al., 2013) assessed subjective exercise intensity using the Borg rating of perceived exertion scale (RPE scale), and participants were instructed to exercise at a predetermined intensity. However, the optimal dosage, duration, and intensity of AE were not identified as most of the studies demonstrated low-to-moderate effect sizes and both AE and LE groups mostly presented comparable results across all trials.

The outcomes were measured using various dynamic balance tests, but the assessments were performed immediately after the interventions were terminated. Although each measurement contains critical components in daily living activities and indirectly predicts the potential risk of falls, the generalization of the results regarding the reduction of fall risks must be interpreted with caution as these are lacking in regards to the long-term effects of the interventions. Therefore, future studies may wish to evaluate dynamic balance in an extended length of time to assess endurance-related muscle functions that are also essential for postural adjustment in daily life. The aim of AE interventions in the older population is to improve physical fitness, functional performance, and postural adjustment to ultimately reduce the risk of falls and fall-related injuries and improve their quality of life. Simmons and Hansen (1996) tracked the rate of injuries between 10-12 months after the termination of the last session and reported that there were no orthopedic injuries from falls in the AE group, whereas there were two bone fractures (16.7%) in the LE group since the last session. Two trials conducted by Pérez de la Cruz (2007, 2008) also included second post-intervention assessments, but the time interval (1-month post-intervention) was not sufficient to determine long-term effects of AE on dynamic balance or fall reductions. Arnold et al. (2008) and Volpe et al. (2014) reported adverse events that occurred during the interventions, but none of the included studies reported participants' feedback for the AE or LE programs. Besides the main outcome measures, supplementary information regarding injuries and psychological effects, such as satisfaction and enjoyment, may be helpful for an in-depth interpretation of the effectiveness of AE.

In consideration of the exercise program components, the results of the meta-analyses that demonstrated AE and LE have equivalent effects on dynamic balance should be interpreted with caution. In general, to improve a specific skill, a completely or nearly identical task is generally included in exercise interventions to induce a practice effect. However, among the ten trials in the meta-analyses, only four trials included at least one balance or gait-related task in the exercise programs (Arnold et al., 2008; Vivas et al., 2011; Volpe et al., 2014; Zivi et al., 2018), and the rest of the ten trials included other types of exercises, such as endurance, strength, mobility, or aerobic exercises, that may contribute to the improvement of dynamic balance. Thus, future research may wish to include a goal-focused exercise program that focuses on balance-related tasks and controls for other variables, such as exercise intensity, to more clearly compare the effectiveness of AE and LE on dynamic balance in the older population.

Clinical implication

This study did not identify the statistical superiority of AE over LE programs on dynamic balance. However, these results imply that AE can be an appropriate alternative to LE which leads to clinically meaningful improvements in balance. Both AE and LE have different advantages. Because LE is performed under dryland conditions and is more associated with activities of daily living, these can be more applicable and transferable to enable older adults to successfully improve practical skills. Due to environmental characteristics, muscle activation patterns and movement kinematics are different during aquatic activities compared to those during identical land activities (Bressel, Louder, Hoover, et al., 2017; Silvers et al., 2014), which may lead to less transferability to various functional tasks on dry land, however, this has not been formally tested or observed in previous research. The aquatic environment provides older adults with numerous biological, neurological, and musculoskeletal advantages and helps them perform higher exercise intensities in a safer and supportive training environment without the risk or fear of falling (Bressel et al., 2011, 2012, 2014; Denning et al., 2010; Garner et al., 2014; T. Louder et al., 2018). Therefore, it is suggested that future studies and practitioners select the proper exercise mode that matches each participant's preference and aim of the intervention to maximize the intervention effectiveness. Further investigations regarding the classification of disorder, disease, or history of falls may provide stronger scientific rationales for future balance training protocols for older adults.

As identified in this review, most of the AE programs were administered by physical therapists in clinical facilities. Because of the limited accessibility of aquatic exercise facilities, availability of experts, and higher medical costs, AEs are not broadly practiced in the senior populations. Thus, more easily accessible and lower-cost AE protocols need to be established so that older adults can participate in various physical activities in a safer environment to improve balance, reduce the risk of falls, and ultimately improve their quality of life.

Study limitations

This systematic review and meta-analysis have several limitations. First, this study was limited to peer-reviewed journal articles published in English and RCT designs only, which may increase the risk of publication bias and potentially exclude appropriate studies with high-quality methodologies. In consideration of the potential small study effects and publication bias, future meta-analyses may want to identify and include unpublished outcomes and unpublished studies to improve the validity of results (Song et al., 2013). Also, we included outcomes using the balance categories instead of using just one measure from each study because we only had 10 studies. Due to the small number of studies included in each category, potential covariates, such as the duration of intervention, exercise type, or exercise intensity, could not be appraised using a moderator analysis. In future reviews, it may be appropriate to use a single measure in each study and conduct a meta-regression to identify the impacts of the potential covariates on the effect sizes in the meta-analyses. In addition, five out of 11 studies in the review presented "somewhat concerns" of risk of bias and four had a "high" risk bias, that potentially cause overestimation of the true effects of AE and LE. The randomization process, missing outcome data, and selection of the reported result were the main causes of bias. Thus, we suggest that future trials make advanced plans for these three categories. Furthermore, as only two outcomes (Simmons & Hansen, 1996; Vivas et al., 2011) in the proactive balance category demonstrated high effect sizes, we were not able to establish the general guideline with optimal exercise type, intensity, dosage, and duration to improve dynamic balance in older adults.

Conclusion

To summarize, AE displays comparable effects on dynamic balance in older adults aged 65 years or older when compared to LE. Thus, AE may be effectively utilized as a safer alternative to LE, but the results should be interpreted with caution due to the limited quantity and risk of bias of the studies. Considering clinical applications, further trials with longer-term outcome measures are needed to elucidate effective AE protocols on balance and falls.

CHAPTER III

COMPARATIVE EFFECTS OF EXERCISE INTERVENTIONS ON REACTIVE BALANCE IN OLDER ADULTS: A SYSTEMATIC REVIEW AND NETWORK META-ANALYSIS

Abstract

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

Design: Systematic review and network meta-analysis (NMA)

Data Sources: Electronic databases (MEDLINE, EBSCO, CINAHL, SPORTDiscus, PsycINFO, PubMed, WorldCat.org, OpenGrey.eu, and PROQUEST) and reference lists were searched from inception to February 2021.

Eligibility Criteria for selecting studies: Older adults aged 65 years or above, randomized controlled trials (RCTs) comparing at least two distinct exercise interventions or one exercise intervention with a no-exercise controlled intervention (NE), at least one measure of reactive balance.

Results: Forty-six RCTs (n=1745) investigating 17 different types of exercise interventions were included, of which 23 (50%) were at some concerns level of risk of bias, 22 (48%) were at high risk, and 1 (2%) was at low risk of bias. Reactive balance training not combined with other types of exercise interventions 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

(SUCRA=0.9; mean difference (95% Credible Interval): 2.7 (1.0 to 4.3)) and in the healthy sample (SUCRA=0.9; 2.9 (0.92 to 4.8)), followed by the power training in the entire sample (SUCRA=0.67; 1.5 (-1.2 to 4.3)) as well as in healthy sample (SUCRA=0.71; 1.9 (-1.8 to 5.5)).

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

PROSPERO registration number: CRD42021256638

Introduction

The World Health Organization (WHO) recently reported that approximately 646,000 individuals accidentally die from falls globally per year, and specifically, older adults aged 65 years or over suffer the greatest number of fatal falls (World Health Organization, 2021). 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 (World Health Organization, 2008). The estimated medical expenditures attributable to either fatal or nonfatal falls are approximately $50 billion per year in the United States population ages 65 or older (Florence et al., 2018), and falls ultimately reduce the quality of life and life satisfaction (Stenhagen et al., 2014). Given the critical economic impacts of falls and their consequences in this population, understanding the prevention and rehabilitation strategies of falls in detail is imperative.

Among various intrinsic risk factors for falls, gait and balance problems have been considered as the strongest risk factors (Ambrose et al., 2013; Deandrea et al., 2010). 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 (Shumway-Cook & Woollacott, 2017). However, older adults show age-related decline in sensorimotor systems, which in turn increases the risks of falls (Mahoney et al., 2019; Osoba et al., 2019). 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 (Y. Kim, Vakula, et al., 2020; Sibley et al., 2021).

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 (World Health Organization, 2008). Notably, slips and trips were the most prevalent causes of falls in regards to circumstances in older adults (W. P. Berg et al., 1997). Reactive balance strategies, such as swaying around the ankle or hip joints, taking a reactive step, or reaching to grasp a handhold (Shumway-Cook & Woollacott, 2017), 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 (Alissa et al., 2020; Okubo et al., 2021).

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 (Bohm et al., 2015; Lesinski et al., 2015; McCrum et al., 2017; Moore et al., 2019). However, there remains some limitations in the prior syntheses. First, the exercise interventions were limited to balance or strength pieces of training despite multiple types of exercises employed for improving reactive balance. Consequently, to the best of our knowledge, none of the previous reviews or meta-analyses have considered 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 (Sibley et al., 2021). Second, the systematic review by Moore et al. (2019) who examined the effectiveness of active physical training interventions on reactive balance did not perform a quantitative synthesis (Moore et al., 2019). 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. 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

This systematic review and meta-analysis was prospectively registered in the PROSPERO database (CRD42021256638). The review was conducted in accordance with the PRISMA extension statement for network meta-analysis (Appendix A) (Hutton et al., 2015).

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, research settings (e.g., community, clinics, and long-term care facilities), or the history of falls. Studies were included, if at least two experimental groups participated in each of the different exercise intervention programs or if there was at least one exercise intervention group with a no-exercise controlled 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. The studies must have included at least one reactive balance assessment, which is defined in this study as an assessment entailing a mechanical postural perturbation given during a static or dynamic steady-state task. The studies included 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 June 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. (Howe et al., 2011) and Sibley et al. (Sibley et al., 2021) were modified in consideration of the purpose of the current research and applied to the coding (Table 3-1). Details of the modified coding framework were described in Appendix B.

Table 3-1

Exercise types

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

Means (M) and standard deviations (SD) for all eligible outcomes of reactive balance measures at baseline and post-intervention were extracted for 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 lapsed without response, the data was 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 software (http://digitizer.sourceforge.net) was applied for data digitization and extraction.

Risk of bias

To ascertain an overall and study-level risk of bias of 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 (Sterne et al., 2019). 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 (Higgins et al., 2019):

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

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 (Bruderer-Hofstetter et al., 2018; Fu et al., 2008; Lai et al., 2018; Wu et al., 2021). 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 (Higgins et al., 2019; Rücker et al., 2017). 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 (Schwarzer et al., 2015). 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 (Dias et al., 2018; Lunn et al., 2000). A random-effects model was used considering the clinical and methodological between-study heterogeneity (Borenstein et al., 2009; Sutton et al., 2000). 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 (Brooks & Gelman, 1998). The convergence was assessed using the trace plot, density plot, and Brooks-Gelman-Rubin diagnostic statistics (Brooks & Gelman, 1998).

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 (MD) to the reference intervention with 95% credible intervals (CrI). 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 (Salanti et al., 2014), was checked using the node-splitting analysis. The first subgroup analysis was performed by the inclusion of studies with healthy older adults (78% of all studies). The second subgroup analysis was conducted by grouping the outcome measures by the types of reactive balance tasks: (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 an 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 software (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 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, but seven studies were additionally excluded from the quantitative analysis due to data not being reported and not irretrievable (S. Kim & Lockhart, 2010; Okubo et al., 2019; Wang et al., 2019), exercise types not included in the network (Allin et al., 2020; Cabrera-Martos et al., 2020), exercise intervention included in only one trial (Lacroix et al., 2016), and no continuous data reported (Beling & Roller, 2009). The schematic flow chart for the selection process is presented in Figure 3-1, and all included studies are listed in Appendix C.

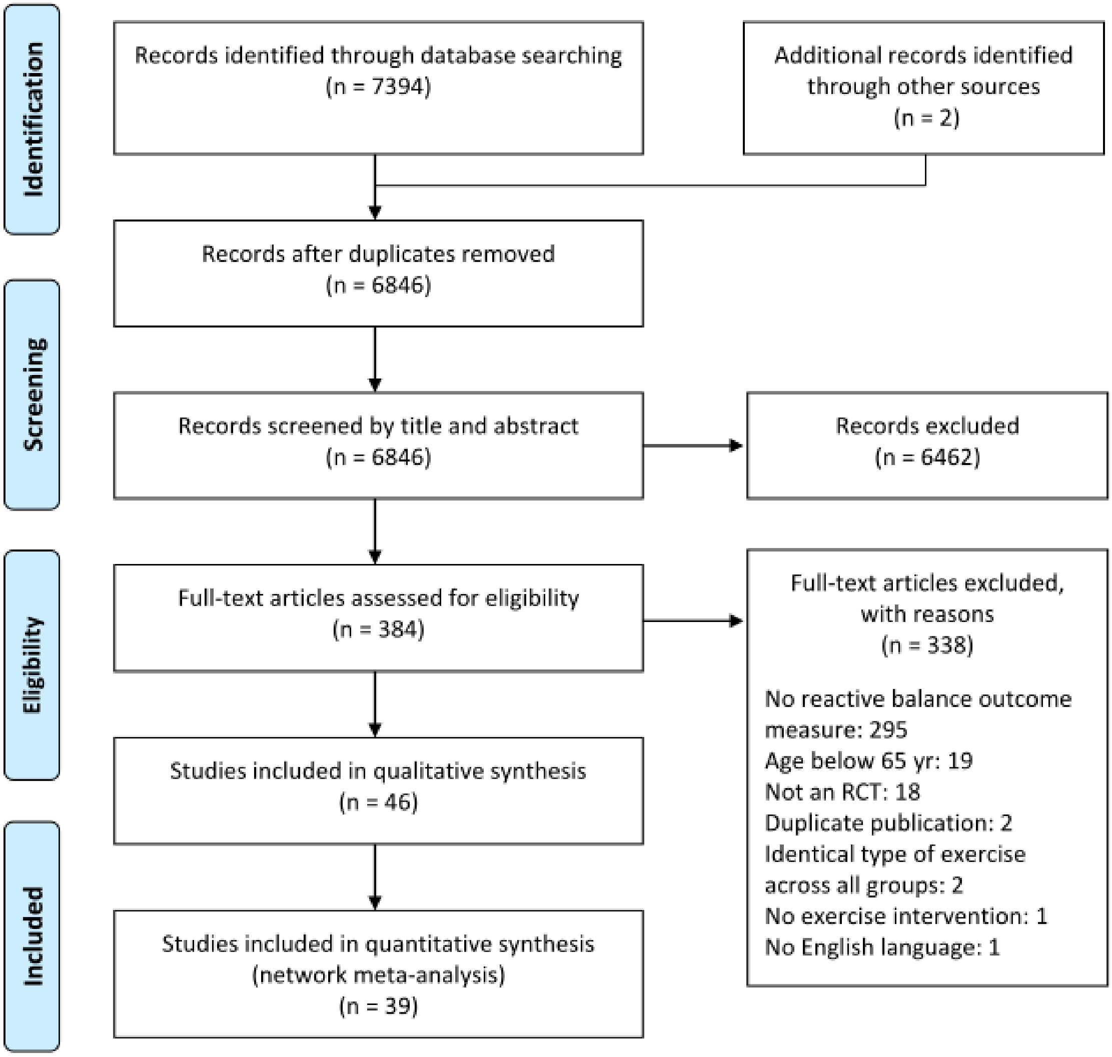


Figure 3-1. PRISMA flow diagram of study selection

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 a task-specific training (i.e., comparable reactive balance task included in the assessment and training) (Arghavani et al., 2020; Beling & Roller, 2009; Bieryla et al., 2007; Jagdhane et al., 2016; Mansfield et al., 2010; Morat et al., 2019; Okubo et al., 2019; Parijat & Lockhart, 2012; Rieger et al., 2020; Wang et al., 2019; Wolf et al., 1997). The characteristics of the studies, including the participants, exercise interventions, outcomes measurements, and main findings are summarized in Appendices D, E, and F.

Risk of bias

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

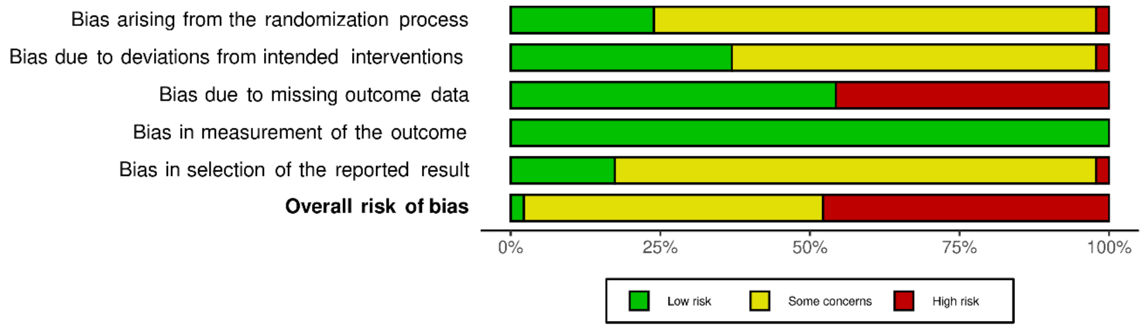


Figure 3-2. Summary of the distributions of the reviewers' judgements across the studies for each risk of bias domain

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 (Cabrera-Martos et al., 2020). 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 (Hatzitaki et al., 2009; Lacroix et al., 2016; Ni et al., 2014); thus, data in these two groups were combined into a single group. Two exercise groups in studies by

Gatts (S. Gatts, 2008; S. K. Gatts & Woollacott, 2007), str and NE groups in studies by Granacher et al. (Granacher et al., 2006, 2009), and two exercise groups in studies by Parijat et al. (Parijat et al., 2015a, 2015b) 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 3-3. 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.

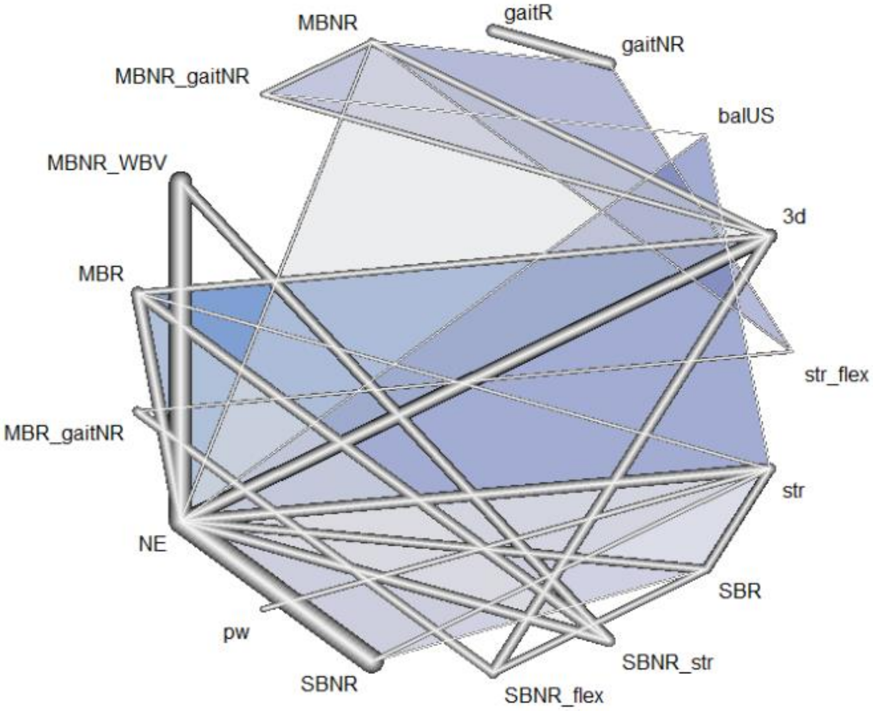


Figure 3-3. Network geometry of the included exercise programs: Each line indicates a direct comparison of two different exercise programs. The thickness of the edge is proportional to the number of direct comparisons in the network. Different exercise types combined in one program are connected via 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 (Appendix H). 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 3-2).

Table 3-2

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.

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 3-4). All exercise interventions resulted in greater improvements when compared to NE; however, SBR, pw, and gaitR demonstrated the largest MD, and 3d, SBNR_str, and gaitNR presented the smallest MD versus NE. The trace plot, density plot, and Brooks-Gelman-Rubin diagnostic statistics showed good convergence. 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 3-2). The results suggest that our main findings regarding the relative effectiveness of each exercise intervention are robust for future decisions.

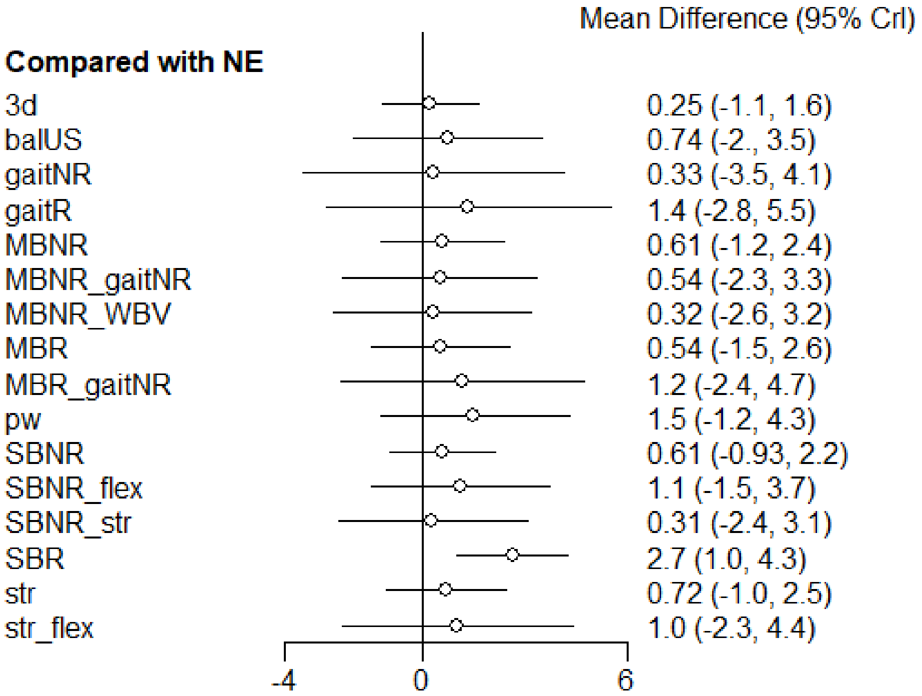


Figure 3-4. Forest plot of the relative effects of exercise interventions with a no-exercise as a reference group. SBR, Single balance exercise including reactive balance component; SBNR, Single balance exercise not including reactive balance component; MBR, Multiple balance exercises including reactive 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 3-5).

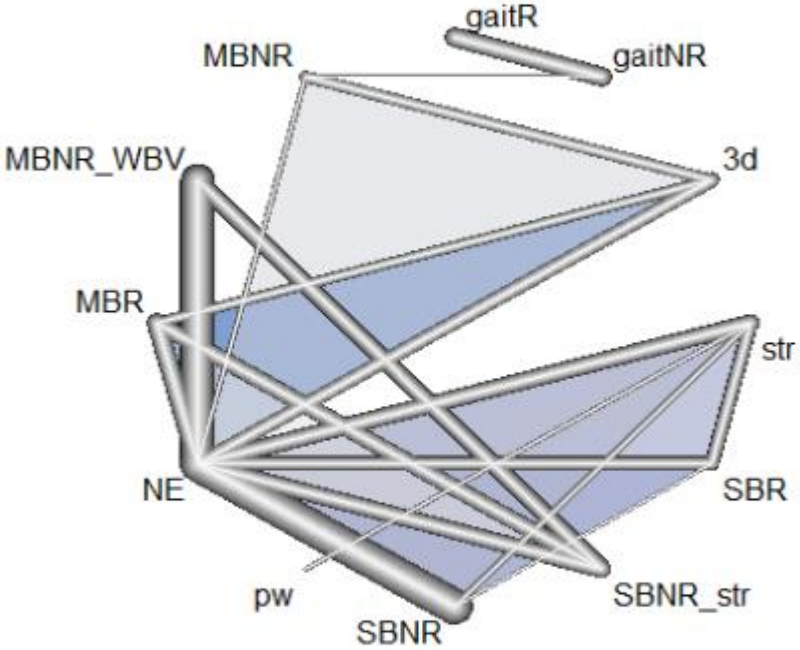


Figure 3-5. Network geometry of the included exercise programs in healthy older adults: Each line indicates a direct comparison of two different exercise programs. The thickness of the edge is proportional to the number of direct comparisons in the network. Different exercise types combined in one program 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 3-3). 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 3-3). The relative effects of all exercise interventions compared to NE were presented in Figure 3-6. A relative effect matrix was additionally created for all comparisons in the healthy older adults (Appendix I). Too few trials in other disease groups were available to conduct further subgroup analysis.

Table 3-3

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.

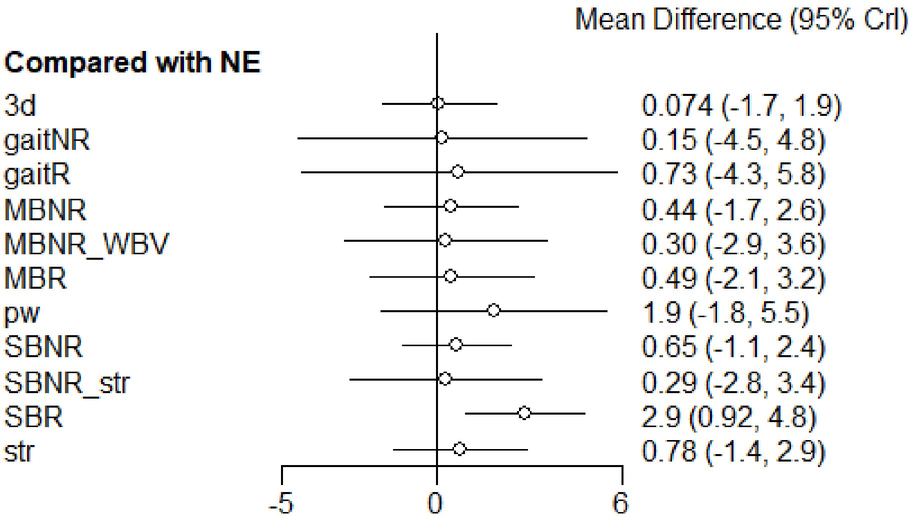


Figure 3-6. Forest plot of the relative effects of exercise interventions with a no-exercise as a reference group in healthy older adults. SBR, Single balance exercise including reactive balance component; SBNR, Single balance exercise not including reactive balance component; MBR, Multiple balance exercises 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.

For the second subgroup analysis regarding the types of reactive balance tasks, the first subgroup was analyzed for gaitR versus gaitNR using a multilevel MA due to insufficient trials in other treatment comparisons, and the second, third, and fourth subgroups were analyzed using NMA. The fifth subgroup was not analyzed due to the sparsity of data. 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 subgroup analyses, 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 3-4 and figure 3-7, respectively.

Table 3-4

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.

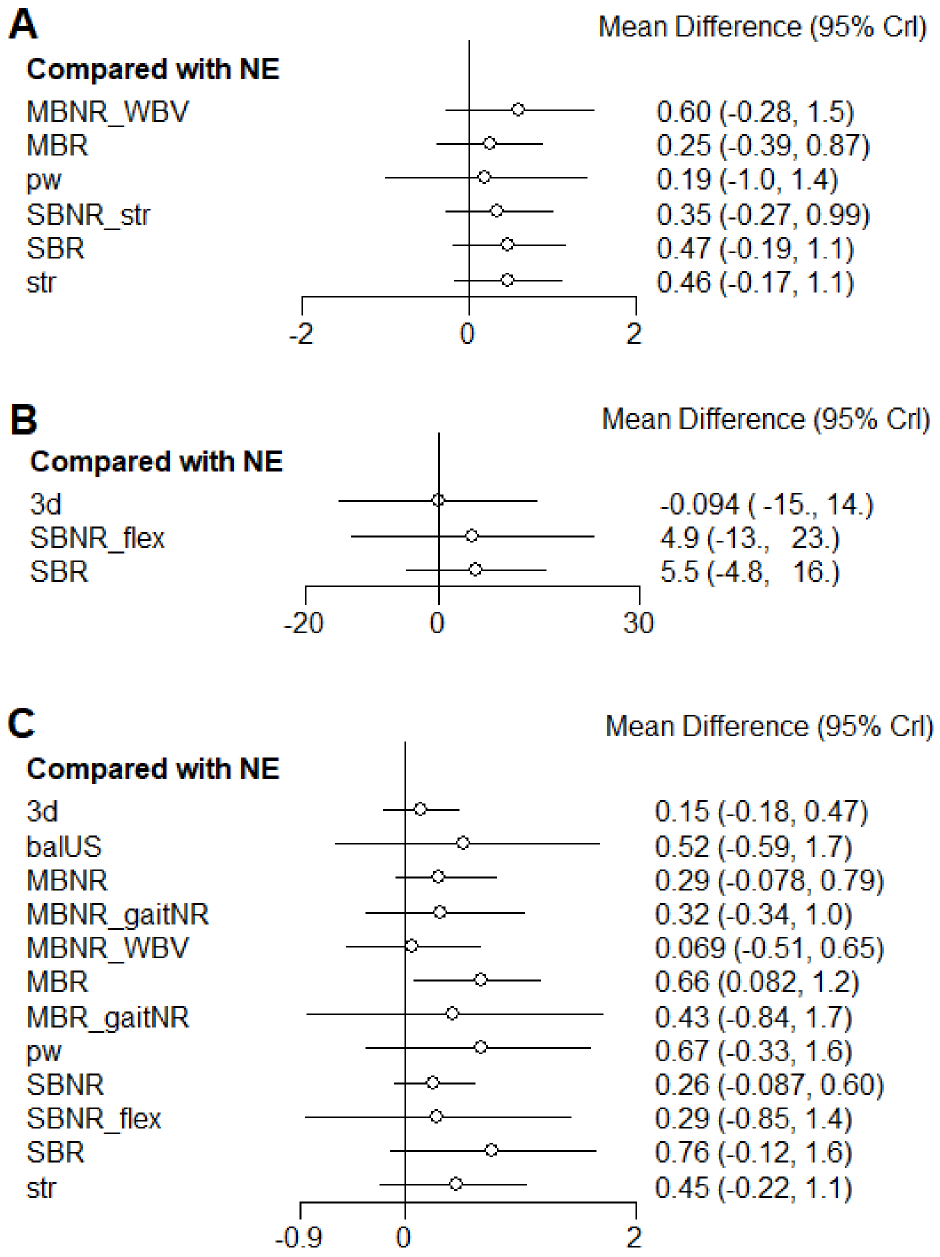


Figure 3-7. Forest plots of the relative effects of exercise interventions with a no-exercise as a reference group in each reactive balance outcome category. A. Simulated forward falls, B. Being pushed or pulled, C. Movable platform. SBR, Single balance exercise including reactive balance component; 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.

Discussion

To our knowledge, this study is the first NMA to determine which type of exercise intervention is most effective at 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 single balance exercise with a reactive balance component confer the most beneficial effects, followed by power training (second) and gait training with a reactive balance component (third), for improving reactive balance.

The results of this current study highlight the importance of applying the principle of specificity to training interventions designed to improve reactive balance. A specific type of balance exercise has no, or at most a limited transfer effect on non-trained balance tasks (Harper et al., 2021; Kümmel et al., 2016). 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 assessed reactive balance performance after training using the same type of reactive balance task (i.e., task-specific reactive balance training) (Allin et al., 2020; Arghavani et al., 2020; Beling & Roller, 2009; Bieryla et al., 2007; Mansfield et al., 2010; Morat et al., 2019; Okubo et al., 2019; Parijat & Lockhart, 2012; Rieger et al., 2020; Wolf et al., 1997). During reactive balance tasks, a mechanical perturbation was given to simulate a real-life situation, such as slipping, tripping, falling, being pushed or pulled by someone, or a moving surface. Because the parameters of the perturbations, such as type, magnitude, direction, and the point of application, were distinctively set up in each reactive balance task, participants required task-specific cognitive processes, muscle synergies, and succeeding kinematic strategies to counteract the perturbation (Chen et al., 2017; Grabiner et al., 2014; Winter et al., 1990). In response to a posterior surface translation, for example, it has been reported that gastrocnemius muscle activity begins at about 90-100 msec after the translation, followed by the hamstrings and paraspinal muscles; whereas, tibialis anterior is activated first, followed by quadriceps, and abdominal muscles in response to a forward surface translation (Shumway-Cook & Woollacott, 2017). The results of the second subgroup analyses with high SUCRA scores of SBR also accentuate the significance of specificity of training. However, the estimates should be interpreted with caution given the small number of trials and several wide credible intervals.

The effectiveness of SBR and gaitR can also be supported in the paradigm of 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 (Izawa et al., 2008). The central nervous system plays a key role in the acquisition and facilitation of the balance recovery (Beck et al., 2007; Bolton, 2015). 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 use the learned models for an efficient and optimized movement plan (Izawa et al., 2008), that ultimately improves compensatory reactions in older adults (Bohm et al., 2015; König et al., 2019). Such motor training is capable to alter corticospinal excitations and reorganize motor maps and synaptic changes in the cerebral cortex, which ultimately facilitates the acquisition of a specific balance recovery skill (Beck et al., 2007; Grabiner et al., 2014), and the neuroplastic changes after training offer revealing clinical insights. However, the reactive balance performances have weak correlations with other balance tasks, such as static/dynamic steady-state balance and proactive balance irrespective of age (Kiss et al., 2018). 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 (Harper et al., 2021).

Three critical principles of exercise training include volume, intensity, and frequency. Here, the volume of exercise should be considered to scrutinize the basis of the relatively less effective multicomponent exercise interventions. Training volume is largely determined by the time commitment (duration) of the training. Proper training volume is specifically imperative in consideration of the 'biological ceiling' which connotes that excessive volume beyond each individual's threshold does not bring further enhancement in functional capacity (Hawley, 2008). The average duration of each training session in this current study 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. (2007), 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 (Burgomaster et al., 2008; Hawley, 2008). 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. It is encouraging that Bhatt and Pai (2009) have demonstrated significant improvements in reactive balance performance after a single high-intensity training session comprised of 24 slip trials. This is particularly noteworthy given that such minimal training effects were retained for several months (Bhatt & Pai, 2009). Considering the aforementioned factors of reactive balance training, future trials will need to identify what environment context and recovery strategies should be targeted to maximize the transfer to real-world scenarios. Then, in the case of multiple purposes in one program, the volume and intensity of each exercise need to be determined by reflecting the priorities of included exercises based on the results of each individual's baseline assessments and specific needs.

Lastly, given the high ranking of power training, the probable inter-relation with reactive balance control 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 (Madigan, 2006). Aging inherently brings loss of motor neurons, associated with apoptosis, and reduction and denervation of muscle fibers, specifically related to type II muscle fibers, and consequently decreases in muscles' capacity to produce maximum muscle strength, power, and rate of force development (Aagaard et al., 2010). Thus, in general, fallers generate less muscle power than non-fallers, and older adults generate less power than young adults (Madigan, 2006; Perry et al., 2007). Power is the product of force and velocity. 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 (Muehlbauer et al., 2015); however, the effectiveness of power training on reactive balance has been explored only in a few, recent trials (Cherup et al., 2019; Inacio et al., 2018; Pamukoff et al., 2014). The results of this current study may have implications for future directions in assessing the relationship as well as mutual effects of muscle power and reactive balance.

Clinical implications

Considering the findings of this study, it would be advisable for clinicians to preferentially include reactive balance training in line with the targeted circumstances and reactions, 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. The possibility of enhancing task-specific neuroplasticity with balance training using external mechanical perturbations has far-reaching clinical and research implications. Therefore, 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.

Strength and limitations

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 (Schwarzer et al., 2015). Thus, the 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 (Cheung et al., 2012). Accordingly, the use of a NMA with a random-effects model in this current study was a strength when it comes to applicability and generalizability. In general, however, 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 (Dias et al., 2018), which was a limitation of this study. 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 (Bogaerts et al., 2007; Wang et al., 2019). 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.

Conclusions

In conclusion, our NMA indicated that SBR, which simulates a real-life fall scenario (e.g., slips or trips) 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.

CHAPTER IV

GENERAL DISCUSSION AND CONCLUSIONS

This dissertation presented two studies that investigated the effects of exercise-based interventions on balance in older adults. First, this dissertation proposed to comparatively evaluate how different exercise modalities (i.e., aquatic and land environments), affect each category of dynamic balance control, including dynamic steady-state balance, proactive balance, and reactive balance, in older adults (Chapter II). Reactive balance is the last line of defense to prevent a fall when the body loses stability. For example, in the case of the controllable (i.e., relatively small) postural perturbations, fixed-support reactions at the ankle and hip joints occur in the earlier phase (Maki & McIlroy, 1997). When the earlier fixed-support reactions are not sufficient to arrest the displacement of the center of mass and recover balance, change-in-support reactions are generated, which are mostly represented by stepping or reach-to-grasp responses (Maki & McIlroy, 1997). Thus, a better understanding of effective exercise-based interventions is guaranteed to formulate future fall prevention programs for older adults. Specifically, a lack of comparisons for the measures of reactive balance in Chapter II suggested a need for additional evidence-based data related to exercise interventions that improve reactive balance. Thus, this dissertation further investigated how reactive balance can be distinctively affected by different types of exercise-based interventions (Chapter III).

In general, this dissertation adopted analytical and statistical approaches using systematic reviews and meta-analyses for synthesizing evidence presented in all available previous trials. Scientific and evidence-based knowledge regarding aging and risks of falls can be advanced on the basis of systematic repetitions by other studies. However, there are several common obstacles to the replication and accumulation of research. First, there is no guideline or specific reference for methodically organizing and synthesizing previous empirical findings (Card, 2011). Consequently, researchers may not be able to be comprehensively informed within the purview of a specific research question, and thus, the need for further research can be overemphasized. Second, previous trials commonly utilize slightly different samples or methodologies rather than exactly replicating one another (Card, 2011). That imperfect replication precludes researchers from identifying which component of the studies accounts for the meaningful differences in the results. One of the promising solutions is the systematic review and meta-analysis. Using that approach, relevant prior research can be identified and critically appraised through qualitative as well as quantitative syntheses. Therefore, results from systematic reviews and meta-analyses are considered the highest level of evidence, and it is strongly recommended to use that evidence for clinical decision making (P. B. Burns et al., 2011). In addition, given the ability of a NMA to summarize comparisons between multifarious exercise-based interventions concurrently, this approach allows for broader exploration and clinical interpretations.

Chapter II compared the effects of aquatic versus land exercises on dynamic balance in older adults. Out of 11 studies, eight reported AE was more effective than LE in at least one measure of dynamic balance, two showed no intergroup differences, and one concluded only one measure of dynamic balance was more improved after LE versus AE. However, surprisingly, the environment-associated differences between AE and LE groups were not detected in any subcategories of dynamic balance in the meta-analysis. Here, the meta-analysis might miss some key indicators of improvements, and potential sources of a type II error can be conjectured. First, the meta-analysis may not have had enough statistical power to detect a statistical difference between AE and LE. Larger samples are usually preferred in experimental studies to reduce sampling error and increase the statistical power. The number of trials included in the meta-analysis was relatively small (ten in total), and only 50% of the original research trials performed power calculation analyses to estimate sufficient sample size for detecting between-group differences, which resulted in the small total sample size in the meta-analysis. Second, the selection of the outcome measurements could probably effect the statistically non-significant differences between AE and LE. Most of the studies provide results from several distinct measures of dynamic balance. Three different categories of measures, such as dynamic steady-state balance, proactive balance, and balance test batteries, were collectively included under the name of the dynamic balance, and the selections of only one outcome variable in each category were based on the importance and relevance to the target population according to previous research. However, the selection process did not consider the nature of the tasks utilized in each exercise intervention, potential similarities between excluded outcome variables, and that the tasks in the interventions might not be reflected in that process. Therefore, future studies may wish to consider ways that will offer high statistical power with respect to the aforementioned potential sources, such as sample sizes and pertinent selection of outcome variables regarding the detailed components of AE and LE interventions.

The second study developed a method for estimating relative effects of various types of exercise-based interventions using a NMA that incorporated direct and indirect estimates in one statistical model. The results generally showed SBR was the highest probability for being the most effective training exercise for improving reactive balance regardless of the clinical (i.e., disease or injury) classifications or the type of reactive balance task (e.g., simulated slip or trip). Power training also demonstrated a high ranking following SBR not only in the complete sample of older adults but also in the healthy older adult sample. However, due to the lack of long-term follow-up measures in most studies, this NMA could not determine how much the training effects were retained after the termination of each intervention. Insufficient follow-up data in regards to the falls also precluded further evaluation of the effects of each exercise intervention on the ultimate goals in their lives, specifically associated with the rate of falls and fall-related injuries, mortality or morbidity rate, and quality of life. Sibley et al. (2021) recently conducted a NMA concerning the comparative effectiveness of exercise interventions on fall-related outcomes, and the most effective combination of exercises for reducing the number of fallers included functional stability limits, dynamic balance, proactive balance, and reactive balance exercises. Especially, both proactive and reactive stepping training significantly reduce falls in older adults by approximately 50% (Okubo et al., 2017). Therefore, the results of the current study and the previous meta-analyses examining fall reductions should be considered concurrently to improve balance as well as to reduce falls in daily life. However, this information should be applied after proper modifications in accordance with the purpose of the intervention. Future research may wish to sequentially explore the effects of different exercise interventions not merely on reactive balance but on the resultant fall-related outcomes in a single trial from a long-term perspective.

In summary, aquatic exercise may be a promising alternative intervention when a participant cannot tolerate a land-based exercise due to any factors related to disease or kinesiophobia. Also, each participant's preferences should be reflected for the selection of the exercise environment given the findings that both AE and LE comparably improve the dynamic balance. In addition, an individualized training program should be considered when the purpose of the intervention is to improve reactive balance in older adults. To determine the components of exercise for the intervention, each participant's performance levels in comprehensive baseline assessments and history of falls, if available, may play a crucial role. In other words, deficits in particular assessments and history of falls, especially related to the mechanism of falls and fall-related injuries in the past, should be considered when prescribing an exercise-based intervention. Thus, the specific types of postural perturbations experienced and consequently, the reactive tasks that need to be improved will be determined and accordingly applied to the training program to improve the reactive balance and fall-related outcomes.

Because there are some advantages of aquatic exercise over land exercise in some populations, and because there is strong evidence that reactive balance is enhanced by means of exercise-based interventions (Moore et al., 2019), there is a need to formally examine if aquatic-based exercises effect positive changes in reactive balance and prevent falls in older adults. The findings of this dissertation suggest the need for this line of research, and it provides additional scientific rationales for future aquatic-based intervention trials aimed at various types of balance control in older adults.

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APPENDICES

Appendix A

PRISMA for Network Meta-Analyses (PRISMA-NMA)

Section/Topic	Item #	Checklist Item	Reported on Page #
TITLE			
Title	1	Identify the report as a systematic review *incorporating a network meta-analysis (or related form of meta-analysis).*	38
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: **Background:** main objectives **Methods:** data sources; study eligibility criteria, participants, and interventions; study appraisal; and *synthesis methods, such as network meta-analysis.* **Results:** number of studies and participants identified; summary estimates with corresponding confidence/credible intervals; *treatment rankings may also be discussed. Authors may choose to summarize pairwise comparisons against a chosen treatment included in their analyses for brevity.* **Discussion/Conclusions:** limitations; conclusions and implications of findings. **Other:** primary source of funding; systematic review registration number with registry name.	38-39
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known, *including mention of why a network meta-analysis has been conducted.*_	40-42
Objectives	4	Provide an explicit statement of questions being addressed, with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	42
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists and if and where it can be accessed (e.g., Web address); and, if available, provide registration information, including registration number.	43
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale. *Clearly describe eligible treatments included in the treatment network, and note whether any have been clustered or merged into the same node (with justification).*_	43

Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	44
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	44
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	44
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	45
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	42, 43, 46-47
Geometry of the network	**S1**	Describe methods used to explore the geometry of the treatment network under study and potential biases related to it. This should include how the evidence base has been graphically summarized for presentation, and what characteristics were compiled and used to describe the evidence base to readers.	48
Risk of bias within individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	46
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means). *Also describe the use of additional summary measures assessed, such as treatment rankings and surface under the cumulative ranking curve (SUCRA) values, as well as modified approaches used to present summary findings from meta-analyses.*	47-48
Planned methods of analysis	14	Describe the methods of handling data and combining results of studies for each network meta-analysis. This should include, but not be limited to: • *Handling of multi-arm trials;* • *Selection of variance structure;* • *Selection of prior distributions in Bayesian analyses; and* • *Assessment of model fit.*	46-48
Assessment of Inconsistency	**S2**	Describe the statistical methods used to evaluate the agreement of direct and indirect evidence in the treatment network(s) studied. Describe efforts taken to address its presence when found.	49
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias,	46, 49

		selective reporting within studies).	
Additional analyses	16	Describe methods of additional analyses if done, indicating which were pre-specified. This may include, but not be limited to, the following: • Sensitivity or subgroup analyses; • Meta-regression analyses; • *Alternative formulations of the treatment network; and* • *Use of alternative prior distributions for Bayesian analyses (if applicable).*_	49
RESULTS†			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	49
Presentation of network structure	**S3**	Provide a network graph of the included studies to enable visualization of the geometry of the treatment network.	53
Summary of network geometry	**S4**	Provide a brief overview of characteristics of the treatment network. This may include commentary on the abundance of trials and randomized patients for the different interventions and pairwise comparisons in the network, gaps of evidence in the treatment network, and potential biases reflected by the network structure.	52
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	51
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment.	51-52, 118-120
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: 1) simple summary data for each intervention group, and 2) effect estimates and confidence intervals. *Modified approaches may be needed to deal with information from larger networks.*	53-55
Synthesis of results	21	Present results of each meta-analysis done, including confidence/credible intervals. *In larger networks, authors may focus on comparisons versus a particular comparator (e.g. placebo or standard care), with full findings presented in an appendix. League tables and forest plots may be considered to summarize pairwise*	54, 151-152

		comparisons. If additional summary measures were explored (such as treatment rankings), these should also be presented.	
Exploration for inconsistency	**S5**	Describe results from investigations of inconsistency. This may include such information as measures of model fit to compare consistency and inconsistency models, *P* values from statistical tests, or summary of inconsistency estimates from different parts of the treatment network.	55
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies for the evidence base being studied.	51-52, 118-120
Results of additional analyses	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression analyses, *alternative network geometries studied, alternative choice of prior distributions for Bayesian analyses,* and so forth).	56-60
DISCUSSION			
Summary of evidence	24	Summarize the main findings, including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy-makers).	61
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review level (e.g., incomplete retrieval of identified research, reporting bias). *Comment on the validity of the assumptions, such as transitivity and consistency. Comment on any concerns regarding network geometry (e.g., avoidance of certain comparisons).*	66
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	67
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review. This should also include information regarding whether funding has been received from manufacturers of treatments in the network and/or whether some of the authors are content experts with professional conflicts of interest that could affect use of treatments in the network.	NA

PICOS, population, intervention, comparators, outcomes, study design.

* Text in italics indicates wording specific to reporting of network meta-analyses that has been added to guidance from the PRISMA statement.

Appendix B

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

Appendix C

List of all included studies

Allin, L. J., Brolinson, P. G., Beach, B. M., Kim, S., Nussbaum, M. A., Roberto, K. A., & Madigan, M. L. (2020). Perturbation-based balance training targeting both slip- and trip-induced falls among older adults: A randomized controlled trial. BMC Geriatrics, 20(1), 205. MEDLINE. https://doi.org/10.1186/s12877-020-01605-9

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Appendix D

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
ssssssGranacher 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

Appendix E

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.

Appendix F

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: <u>Adaptive</u> = no falls and less than 2/5 trials in abnormal range; <u>Maladaptive</u> = no falls and greater than 2/5 trials in abnormal range; <u>Unable to Adapt</u> = 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	Motor Control Test (latency of reaction, response	<u>Motor Control Test</u>: Exercise had no effect on latency for any

	forward and backward platform translation while standing), Adaptation Test	strength), Adaptation Test (capacity to minimize postural sway after the perturbation)	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	Both exercise groups, but not group 3, showed improvements in general.

		increase in BOS, maximum voluntary isometric knee extension and ankle plantarflexion moment	
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	(1) summed oscillations of the platform in ML and AP	Group 1 and 2 showed improvements in the clinical push

	transverse plane while standing (2) Clinical push and release test	directions; and (2) the number of steps and quality of the recovery	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 reactions**: backward step displacement, lateral step displacement.	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.
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	Both groups showed extended step length and increased peak EMG of knee flexor and extensor muscles. Group 1 showed increased step

		contact), EMG onset times, timing of first-peak EMG amplitude, and normalized peak EMG amplitude of RF, VL, BF, TA, LG	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	Laboratory-	Incidence of falls during	Group 1 showed a reduced

2015b	induced slip while walking	testing, slip distance, peak sliding heel velocity	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)	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

	of a platform while standing on the Chattexc Balance System		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.

Appendix G

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

Appendix H

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

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**

Appendix I

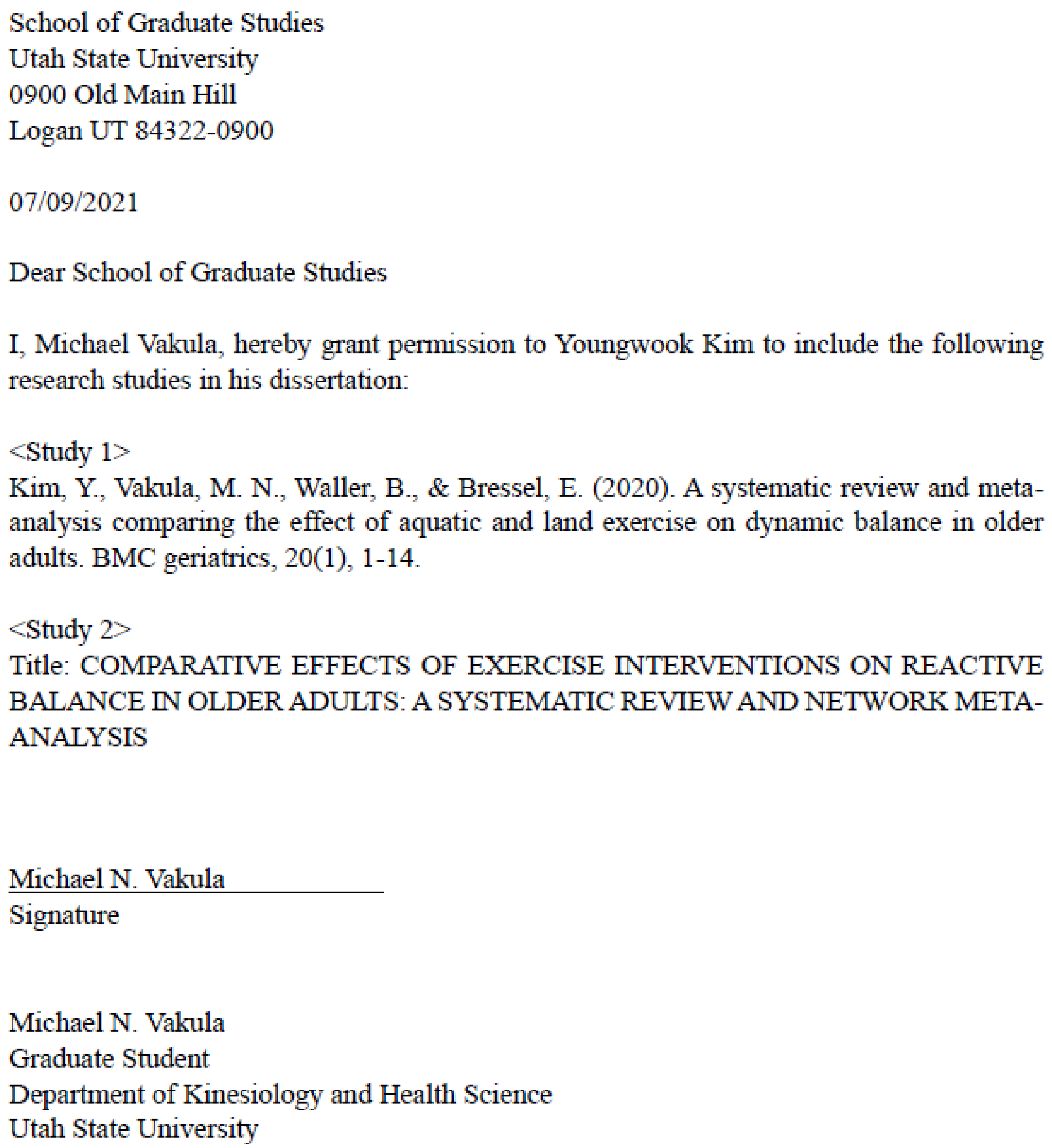
Relative effect estimates with 95% credible intervals of all pairs of exercise interventions in healthy older adults

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

Appendix J

Permission-to-use letters

Permission-to-use letter from Michael Vakula



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07/09/2021

Dear School of Graduate Studies

I, Michael Vakula, hereby grant permission to Youngwook Kim to include the following research studies in his dissertation:

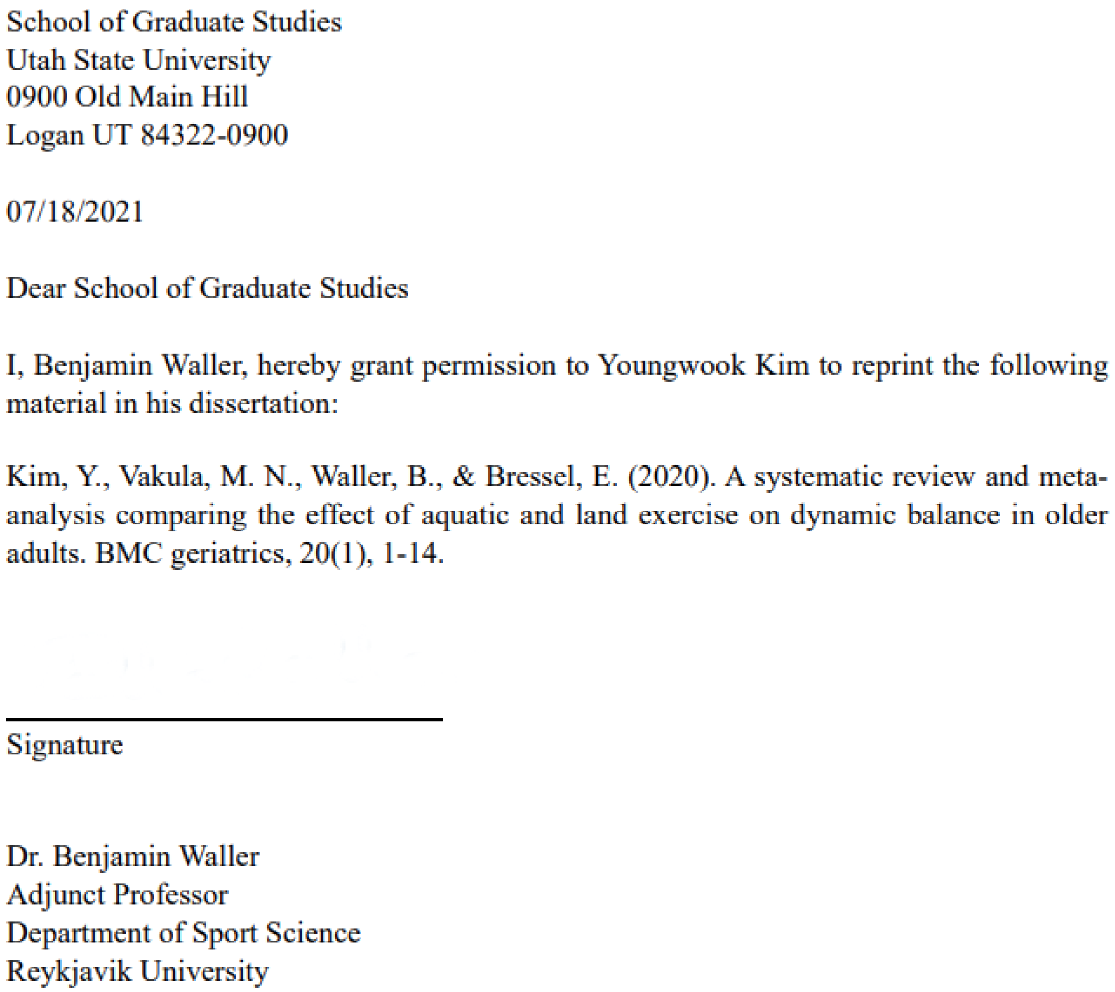
<Study 1>
Kim, Y., Vakula, M. N., Waller, B., & Bressel, E. (2020). A systematic review and meta-analysis comparing the effect of aquatic and land exercise on dynamic balance in older adults. BMC geriatrics, 20(1), 1-14.

<Study 2>
Title: COMPARATIVE EFFECTS OF EXERCISE INTERVENTIONS ON REACTIVE BALANCE IN OLDER ADULTS: A SYSTEMATIC REVIEW AND NETWORK META-ANALYSIS

Michael N. Vakula
Signature

Michael N. Vakula
Graduate Student
Department of Kinesiology and Health Science
Utah State University

Permission-to-use letter from Benjamin Waller



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Kim, Y., Vakula, M. N., Waller, B., & Bressel, E. (2020). A systematic review and meta-analysis comparing the effect of aquatic and land exercise on dynamic balance in older adults. BMC geriatrics, 20(1), 1-14.

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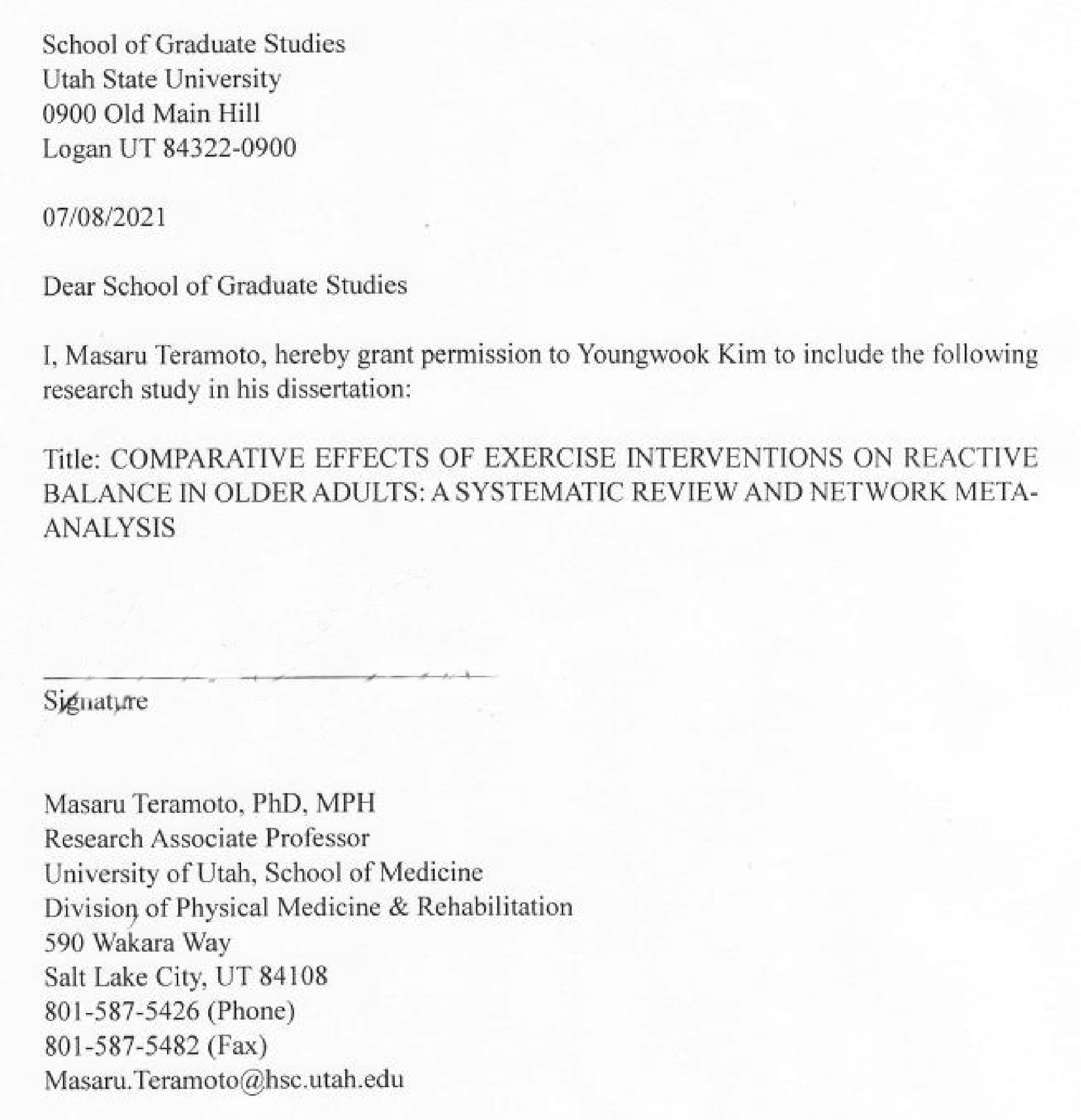
Permission-to-use letter from Masaru Teramoto



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PUBLICATIONS

Manuscripts in Refereed Journals:

Kim, Y., Vakula, M. N., Waller, B., & Bressel, E. (2020). A systematic review and meta-analysis comparing the effect of aquatic and land exercise on dynamic balance in older adults. BMC Geriatrics, 20(1), 1-14.

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Kim, Y., & Rosen AB. (2019). Long-Term Characteristics of Injured Shoulders in Overhead Sports: A Gender Comparison. *Medicine & Science in Sports & Exercise, 51(6),* 877

Kim, Y., Wellsandt, E., Lee, J. M., & Rosen, A. B. (2018). Relationship between Range of Motion, Strength, Upper Quarter Y-balance Test and a History of Shoulder Injury among NCAA Division 1 Overhead Athletes. *Journal of Athletic Training (Supplement), 53(6s),* S-17.

PRESENTATIONS

Academic Conferences:

Vakula, M. N., **Kim, Y.,** & Bressel E. Effects of the Aquatic Environment on Maximal Isometric Muscle Strength and Rate of Force Development. 2020 National Strength and Conditioning Association Conference (online gallery). July 2020.

Kim, Y., Vakula, M. N., & Bressel, E. Is Maximal Isometric Muscle Strength Altered during Water Immersion? 2020 National Strength and Conditioning Association Conference (online gallery). July 2020.

Kim, Y., Rech, N., Talin, L., Bressel, E., & Dolny, D. Intramuscular Temperature of Rectus Femoris during and after Cold-Water Immersion: A Gender Comparison. 2020 National Athletic Trainers' Association Virtual Clinical Symposia. July 2020.

Kim, Y., Vakula, M. N., & Bressel, E. Effectiveness of Aquatic Exercise on Dynamic Balance in Older Adults: A Systematic Review and Meta-analysis. 2020 American College of Sports Medicine Virtual Experience, June 2020.

Kim, Y., & Rosen, A. B. Gender-specific Differences in Upper Quarter Closed Kinetic Chain Performance after Return to Play in Overhead Athlete. National Athletic Trainers' Association Annual Meeting and Clinical Symposium, Las Vegas, NV, June 2019.

Kim, Y., & Rosen, A. B. Long-Term Characteristics of Injured Shoulders in Overhead Sports: A Gender Comparison. American College of Sports Medicine 66th Annual Meeting, Orlando, FL, May 2019

Dakin, C.J., Kern, A., Elwood, M., Vakula, M. N., **Kim, Y.**, & Bressel, E. Vestibular Contribution to Balance Control during Stair Negotiation and Locomotion. Neuroscience 2018 Conference, San Diego, CA, Nov 2018.

Kim, Y., Vakula, M. N., Bolton, D. A., Dakin, C. J., & Bressel, E. Effects of Partial Water Immersion on Immediate and Delayed Memory Recall. 15th World Aquatic Health Conference, Charleston, SC, Oct 2018

Vakula, M.N., **Kim, Y.,** Bolton, D. A., Dakin, C.J., & Bressel, E. Peak Grip Strength Capacity is Higher during Water Immersion. 15th World Aquatic Health Conference, Charleston, SC, Oct 2018

Kim, Y., Wellsandt, E., Lee, J. M., & Rosen, A. B. Relationship between Range of Motion, Strength, Upper Quarter Y-balance Test and a History of Shoulder Injury among NCAA Division 1 Overhead Athletes. National Athletic Trainers' Association Annual Meeting and Clinical Symposium, New Orleans, LA, June 2018

Kim, Y., Gaballah, A., Elgeidi, A., Abd-Elghany, A., Shakrah, N., & Bressel, E. Aquatic Exercise Improves Human Growth Factor Concentrations after Rehabilitation of Hamstring Injuries. 5th International Conference on Evidence-Based Aquatic Therapy, Las Vegas, NV, April 2018

Kim, Y., Lee, J. M., Wellsandt, E., & Rosen, A. B. Effects of Shoulder Injuries on Shoulder Characteristics and Dynamic Balance after Rehabilitation and Return to Play. Rocky Mountain Athletic Trainers' Association Annual Meeting and Clinical Symposium, Salt Lake City, UT, April 2018

Kim, Y., & Yentes, J. Effects of Height Increasing Heel Insole on Lower Extremity Joint Mechanics. University of Nebraska at Omaha Annual Student Research and Creative Activity Fair, Omaha, NE, March 2017

Invited Lecture:

Kim, Y. Introduction of Network Meta-analysis and application using R. HDFS 7200: Meta-Analysis and Literature Review, Department of Human Development and Family Studies, Utah State University, April 2021.

Kim, Y. Functional anatomy and biomechanics of lower extremity. PEP 3250: Anatomical Kinesiology, Department of Kinesiology and Health Science, Utah State University, November 2017.

STUDENT MENTORSHIP

Maggie Rios (2021)	MS Kinesiology, Utah State University, Logan UT *Supported Maters Plan B thesis project*

AD HOC REVIEWER

- Gait & Posture (2021)
- The Physician and Sportsmedicine (2021)
- Journal of Athletic Training (2021)
- World Journal of Psychiatry (2021)
- World Journal of Clinical Cases (2020)

FELLOWSHIP / AWARDS / SCHOLARSHIPS

2021	• Student Research Award American College of Sports Medicine: Biomechanics Interest Group Amount: $400
2021	• Graduate Research Assistant of the Year Kinesiology and Health Science, Utah State University
2020	• Open Access Publication Award Funding source: Utah State University Libraries Amount: $2,565
2019	• Academic travel scholarship Funding source: Force and Motion Foundation Amount: $1,000
2019	• Board fellowship

	Funding source: National Swimming Pool Foundation Amount: $2,000
2019	• Travel grant Funding source: Department of Kinesiology and Health Science & Research and Graduate Studies, Utah State University, USA Descriptions: 2019 ACSM 66th Annual Meeting Amount: $600
2018	• Academic travel scholarship Funding source: Force and Motion Foundation Amount: $500
2018	• Travel grant Funding source: Department of Kinesiology and Health Science & Research and Graduate Studies, Utah State University, USA Descriptions: 2018 NATA 69th Clinical Symposia & AT Expo Amount: $600
2018	• Travel grant Funding source: Department of Kinesiology and Health Science & Research and Graduate Studies, Utah State University, USA Descriptions: 5th International Conference for Evidence Based Aquatic Therapy Amount: $600
2015-2017	• UNO Advantage Scholarship, University of Nebraska at Omaha
2008, 2010, 2011	• Merit Scholarship, Yeungnam University

CLINICAL EXPERIENCE

May-August, 2018	Athletic training internship, Sports Medicine team (football), University of Maryland, College Park, MD

EXTRACURRICULAR AND SERVICE ACTIVITIES

2019-2020	• Doctoral student representative, Department of Special Education and Rehabilitation, Utah State University, Logan, UT
2019-2021	• Research presentation judge, Utah State University Student Research Symposium, Utah State University, Logansss, UT
August 2015	• Medical staff, Nebraska State Taekwondo Competition at Omaha, Omaha, NE
July 2015	• Medical staff, FIVB volleyball tournament and High School Volleyball Challenge, Omaha, NE

CERTIFICATIONS / PROFESSIONAL MEMBERSHIPS

Certifications:

2019	Basic Life Support for Healthcare Providers, American Red Cross
2017	BOC Certified Athletic Trainer, National Athletic Trainers’ Association
2015	CPR/AED For Professional Rescuers with First Aid, American Red Cross

2013	Special School Teacher of Physical Education, Korean Ministry of Education, Republic of Korea
2011	Lifeguard, Korean Red Cross, Republic of Korea
2010	Grade II of Swimming Instructor, Korean Ministry of Culture, Sports, and Tourism, Republic of Korea

Professional Memberships:

2018-Present	American College of Sports Medicine
2017-Present	Rocky Mountain Athletic Trainers' Association
2015-Present	National Athletic Trainers' Association
2015-2017	Mid-America Athletic Trainers' Association
2015-2017	Nebraska State Athletic Trainers' Association