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Aerobic, Resistance, and Isometric Exercise to Reduce Blood Pressure Variability: A Network Meta-Analysis of 15 Clinical Trials

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ABSTRACT

Elevated blood pressure variability (BPV) is an emerging independent risk factor for increased cardiovascular diseases (CVD). Many studies are exploring the impacts of regular physical exercise on reducing BPV. This study aimed to investigate whether exercise can be an intervention to control for the short-term and long-term BPV. A literature search was conducted on MEDLINE, Embase, and PsycINFO on February 10, 2025. The clinical trials and other observational studies that investigated the effects of exercise on systolic and diastolic BPV were included. There were no limitations on age, blood pressure (BP) category, or the use of antihypertensive medication. Mean differences and standard deviations (SDs) of the BPV measurements were extracted to derive standardized mean differences (SMD) with a 95% confidence interval (CI). The heterogeneity was assessed by $I^{2,}$ and random-effect models were performed. Our search identified 8359 studies, of which 25 studies reported BPV outcomes. Fifteen clinical trials compared the short-term BPV among participants with or without exercise. Exercise interventions can significantly reduce both systolic BPV (SMD [95% CI] = −0.37[−0.61 to −0.12]) and diastolic BPV (−0.48 [−0.72 to −0.23]). The benefits are stronger for those with hypertension. Different types of exercise were compared in the network meta-analyses, and aerobic exercise showed more benefits than other types of exercise to improve BPV, especially on the diastolic BPV when it was compared with no exercise (−2.52 [−4.05 to −0.99]). No evidence was observed for the long-term BPV. Exercise interventions effectively reduce the variability of both systolic and diastolic blood pressure (DBP). Aerobic exercise is shown to be more effective in reducing diastolic BPV versus no exercise.

1 | Introduction

There has been growing interest in the impact of exercise on blood pressure variability (BPV), which refers to the fluctuations in blood pressure (BP) levels throughout the day or month [1]. Emerging research suggests that excessive BPV is associated with an increased risk of cardiovascular diseases (CVD), such as dementia, target organ damage, stroke, heart attacks, heart failure, and even mortality [2, 3, 4]. Thus, BPV itself can be an independent risk factor for CVD beyond hypertension [5]. Pharmacological treatment is a mainstay of hypertension management. Antihypertensive medications such as calcium channel blockers, angiotensin-converting enzyme inhibitors (ACEIs), angiotensin receptor blockers (ARBs), and beta-blockers are typically used to treat high BPV [6]. However, regular exercise is an important non-pharmacological component of BP management. It positively affects overall health status and promotes weight management and stress reduction. It also typically has fewer side effects compared to medications, which can sometimes cause adverse reactions or interactions with other drugs.

Regular physical exercise has long been recognized as a fundamental pillar of a healthy lifestyle, contributing significantly to the promotion of cardiovascular health [7] and reducing the risk of developing various chronic diseases, such as heart disease [8], stroke [9], type 2 diabetes [10], peripheral artery disease [11], and hypertension [12]. Exercise enhances the efficiency and capacity of the cardiovascular system by strengthening the cardiac muscles and improving their ability to pump blood, promoting the dilation of blood vessels, reducing resistance in the arteries, and improving the function of the endothelium [13]. It also has consistently demonstrated positive effects on weight management [14], body fat reduction [15], and the control of low-density lipoprotein (LDL) cholesterol [16] and glucose [17]. Exercise interventions have been categorized into three major types: aerobic exercises, involving rhythmic and continuous movements that increase heart rate, respiratory rate, and oxygen consumption; resistance exercises, involving muscle contractions against external resistance; and isometric exercises, characterized by static muscle contractions against body weight [18]. Various types of exercise have been investigated for their impacts on cardiovascular health and BP, with significant reductions observed in resting systolic blood pressure (SBP) and diastolic blood pressure (DBP) [19]. Exercise has been shown to benefit BP management. Recent studies highlight the significant impact of various exercise modalities on BP management in hypertensive patients. Large-scale meta-regression has shown that Structured aerobic exercise is effective in lowering both systolic and DBP in patients with hypertriton [20]. Although a network meta-analysis summarized isometric exercise as particularly effective, suggesting its role as a potent intervention for lowering resting BP [21].

Current evidence suggests that exercise, as a non-pharmacological intervention, also plays an important role in reducing BPV and consequently improving cardiovascular health. A recent meta-analysis reports Aerobic exercise and combined training were the most recommended exercise types improved BPV [22], but the method is limited by the overall comparison of exercise. This study used network meta-analysis comparing different types of exercises on BP management. To summary, the primary objective of this study is to investigate whether exercise can be an intervention to control short-term and long-term BPV. The secondary objective is to compare aerobic resistance and isometric exercise to reduce BPV exercise for BPV management.

2 | Method

2.1 | Study Design

This systematic review and network meta-analysis adhere to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines. It was registered with PROSPERO, and the protocol can be accessed at PROSPERO under CRD42024576977.

2.2 | Literature Search

A comprehensive literature search was performed using the electronic databases of MEDLINE, Embase, and PsycINFO from inception to February 10, 2025. The search strategy incorporated MeSH terms related to BPV and exercise, including "Aerobic Exercise," "Resistance Training," "Isometric Exercise," "Stretching Exercise," and "Physical Training" (Table S1). A supplementary search was conducted on Google Scholar on March 18th, 2025, using the same keywords, in which the first 10 pages of all search records were screened.

2.3 | Inclusion and Exclusion Criteria

Inclusion criteria were: (1) a structured training program involving regular exercise during the intervention period; (2) use of pre-post self-comparison or non-exercise control group for comparison, such as usual care or maintaining daily physical exercise; (3) standard deviation (SD) or coefficient of variation (CV) or average real variability (ARV) were calculated for BPV; (4) BP was measured twice using either office BP or 24-h ambulatory blood pressure monitoring (ABPM) at baseline and after intervention period separately; and (5) study design was experimental studies including pre-post/three arm/randomized controlled trials (RCTs) or cross-over RCT or observational studies including cross-sectional studies and cohort studies. Exclusion criteria were: (1) intervention programs that combined exercise with medication use; (2) studies on post-surgery recovery; (3) studies with no full-text manuscript available; (4) studies that could not extract usable data from the original paper; (5) studies on animal; and (6) studies published in languages other than English.

2.4 | Data Extraction and Risk of Bias Assessment

Two independent reviewers (Z.H. and J.Y.T.) conducted the screening and extraction of all study records obtained from the literature search, adhering to the predefined inclusion and exclusion criteria. After screening the title and abstract, the full text was retrieved for full-text review. A standardized Excel form was utilized for the extraction of basic information and outcomes. The basic information was related to three domains: (1) study backgrounds: Author' name, year of publication, study region, and study design; (2) characteristics of participants, including age, gender, and medication history; and (3) exercise training structuration, indicating intervention frequency and duration, exercise type. Any discrepancies or disagreements encountered during the screening and extraction process were resolved by a third reviewer (A.S.L.).

2.5 | Intervention

Exercise interventions were categorized into the major types of aerobic, resistance, and isometric exercise [18]. Aerobic exercises

TABLE 1 | Classification of aerobic, resistance, and isometric exercises.

Category	Description	Example
Aerobic exercise	Rhythmic and continuous movements that increase heart rate, respiratory rate, and oxygen consumption, also known as cardiovascular exercise	Walking, jogging, cycling, swimming, and High-intensity interval training (HIIT)
Resistance exercise	Strength training or weightlifting, involves using resistance or external weight to perform repetitive muscle contraction training, typically using weights or resistance machines.	By free weights (such as dumbbells and barbells), weight machines, resistance bands, or body weight.
Isometric exercise	Strength training that involves static muscle contractions without any significant joint movement.	Planks, wall sits, and static contractions push or pull against an immovable object.
Combined exercise	Full-body, strength and conditioning program that combines core training, weightlifting, cardio, gymnastics, and several additional elements to improve muscle tone and overall body composition.	Training with aerobic exercise plus additional resistance or isometric exercise, planning with heart-rate focus.
No exercise	Maintain daily activities without exercise.	Usual care

describe regimens that are rhythmic and continuous movements that increase heart rate, respiratory rate, and oxygen consumption. Resistance exercise involves repetitive motions to make the muscle contract against resistance from external weights or machines. Isometric exercises describe static muscle contraction exercises against the body weight. Some training programs combined multiple types of exercise, so a category of combined exercise was included (Table 1).

2.6 | Measurement of BPV

Short-term BPV with ABPM is an automated method of assessing 24-h BP. ABPM should be performed without strenuous activity and with the cuff placed on the non-dominant arm. On the day of ABPM, participants are asked to carry out their usual activities and take medications, but are not allowed to exercise for 24 h. Monitoring is performed with a single measurement interval of 10–20 min during the daytime and a single measurement of 15–30 min at nighttime. The definition of daytime and nighttime varies slightly between studies. A minimum of 20 valid daytime BP readings and 7 nighttime BP readings are required [23].

Long-term BPV refers to measurements taken at the same time each day over a follow-up period of weeks to years. Measurements were taken while the participant was sitting and resting for 15 min or more. BPV can be calculated from a set of BP measurements, based on SD, CV, or ARV.

2.7 | Statistical Analysis

Mean differences and SDs of the BPV were extracted from each study. Standardized mean differences (SMD) were used to combine different assessment scales. The heterogeneity was assessed by I^2. The fixed effect Mantel-Haenszel model was used if $I^2 < 50\%$, which reflects that the variation across studies was mainly due to sampling error. Random effect DerSimonian-Laird meta-analysis was used if $I^2 > 50\%$, which means the variation was mainly due to heterogeneity. Meta-analysis was performed with Review Manager (Version 5.4.1), and the Bayesian network meta-analysis was conducted with R Studio (Version 4.2.2). The results were shown in forest plots and network Diagrams. The SMDs with 95% confidence intervals (95% CI) were used to summarize the findings. Subgroup analysis for the participants with or without hypertension was conducted. Studies with a single-arm design with BPV comparison before and after exercise interventions or studies that reported long-term BPV were extracted to compare the main findings from this study.

2.8 | Quality Assessment

The Cochrane RoB 2.0 (Risk of Bias 2.0) tool was used to assess the risk of bias in RCTs by evaluating domains such as randomization and outcome measurement. This tool enhanced the reliability of research findings. GRADE (Grading of Recommendations Assessment, Development, and Evaluation) complemented it by assessing evidence quality and recommendation strength.

3 | Result

3.1 | Literature Search

A total of 9238 literature records were identified from the databases. Titles and abstracts of 6169 potential studies were screened after removal of duplicated search records across the databases (Figure 1). The full-text review was conducted on 122 relevant articles with exercise intervention on BPV. After exclusion of the studies with insufficient details on exercise interventions or BPV outcomes, 25 papers were included. Ten studies were either in a single-arm design or only reported the long-term BPV; therefore, 15 [24–38] clinical trials were included

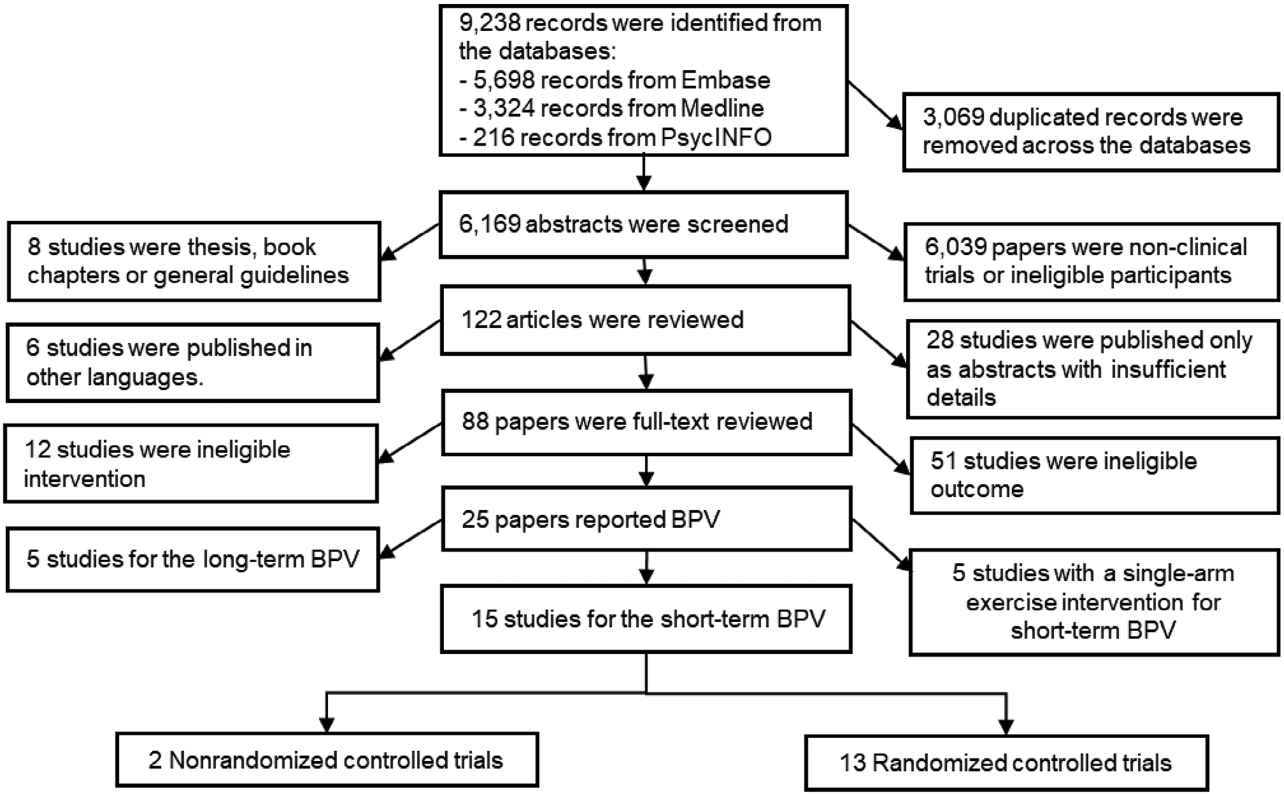

FIGURE 1 | Flowchart for study identification.

as the main analysis. These studies were mainly conducted in the western regions, including the United Kingdom, Germany, Italy, Spain, Switzerland, and Brazil, and one study was from India. A total of 945 participants were included, with a mean age of 50 years and 62% male. Eight of the 15 trials (53%) were conducted on hypertensive patients. Aerobic, isometric, and combined exercise interventions were reported with different intensities and durations (Table 2). The Risk of Bias 2 assessment was shown in Figure S1. The publication bias was assessed using funnel plots (Figure S2).

3.2 | Exercise Benefits on Short-Term BPV

Fourteen out of 15 trials (93%) compared exercise interventions against usual care without exercise, including seven studies on aerobic exercise, four studies on isometric exercise, and two studies on combined exercise. Three studies [28, 31, 38] compared different types of exercise, and a study [29] compared different aerobic levels of training (Table 2). Eleven studies suggested two to three sessions of training per week. The duration of exercise sections ranged from 12 to 80 min. The meta-analysis shows that exercise can significantly reduce both systolic BPV (SMD [95% CI] = −0.37 [−0.61 to −0.12], GRADE = moderate) and diastolic BPV (−0.48 [−0.72 to −0.23], GRADE = moderate) (Figure 2). When different types of exercise were compared in a network meta-analysis (Table S2), aerobic exercise demonstrated a potential reduction in both systolic and diastolic BPV compared to other types of exercise. A significant finding was observed in the reduction of diastolic (−2.52 [−4.05 to −0.99]) Table 3). The Network plot across different types of exercise is shown in Figure S3. More details on the GRADE assessment were shown in Table S3.

3.3 | Subgroup Analysis for Hypertensive Participants

Eight out of 15 trials (53%) compared exercise interventions against usual care without exercise among the participants with hypertension, including six studies on aerobic exercise, one study on isometric exercise, and one on resistance, isometric, and combined exercise. The meta-analysis shows that exercise can significantly reduce both systolic BPV (SMD [95% CI] = −0.95 [−1.28 to −0.62]) and diastolic BPV (−0.79 [−1.21 to −0.38]) (Figure S4). When different types of exercise were compared in a network meta-analysis, aerobic exercise showed a potential reduction in both systolic and diastolic BPV compared to other types of exercise; however, none of these differences were statistically significant (Table S2).

3.4 | Subgroup Analysis for Non-Hypertensive Participants

Seven out of 15 trials (47%) compared exercise interventions against usual care without exercise among the participants without hypertension, including four studies on aerobic exercise and three studies on isometric or combined exercise. The meta-analysis shows that exercise can marginally reduce diastolic BPV (SMD [95% CI] = −0.31 [−0.59 to −0.03]), but not for systolic BPV (Figure S5). In the network meta-analysis, a similar conclusion

TABLE 2 | Characteristics of eligible studies for short-term blood pressure variability.

Author, Year	Country	Mean Age (Years)	Male	Hypertensive Patients	Comparison of Exercise (No. of Participants)	Exercise Intensity	
						Time x Frequency	Duration
Galetta 2006[1,2]	Italy	65	NA	No	Aerobic (30) vs No exercise (28)	Long-term Regular	40 years
Farpour-Lambert 2009	Switzerland	9	30%	No	Combined (22) vs No exercise (22)	60 min x 3 times/week	3 months
Pagonas 2014	Germany	67	43%	Yes	Aerobic (33) vs No exercise (33)	30 min x 3 times/week	2-3 months
Taylor 2019[3]	UK	44	NA	Yes	Isometric (24) vs No exercise (24)	14 min x 3 times/week	1 month
Anasuya 2020[1]	India	31	65%	No	Aerobic (40) vs No exercise (40)	Long-term Regular	28 months
Betolaza 2020	Spain	54	64%	Yes	Aerobic (179) vs No exercise (52)	20-45 min x 2 times/week	4 months
Caminiti 2021	Italy	68	100%	Yes	Aerobic (27) vs Combined exercise (27)	80 min x 3 times/week	3 months
Chehuen 2021	Brazil	62	100%	No	Aerobic (19) vs No exercise (16)	30 min x 2 times/week	3 months
Jamie 2021	UK	23	49%	No	Aerobic (21) vs No exercise (20)	3 times/week	1 month
Seidel 2021	Germany	61	38%	Yes	Aerobic (19) vs Isometric (24) vs no exercise (23)	30 min x 3–5 times/week	3 months
Baross 2022[3]	UK	23	64%	No	Isometric (13) vs No exercise (12)	14 min x 3 times/week	2 months
Bertoletti 2022	Italy	57	49%	Yes	Isometric (36) vs No exercise (36)	12 min x 1 section	1 day
Domingues 2022	Brazil	48	50%	Yes	Aerobic (22) vs No exercise (22)	45 min x 1 section	1 day
Baross 2024[3]	UK	22	59%	No	Isometric (13) vs No exercise (9)	14 min x 3 times/week	2 months
Sousa 2024	Brazil	53	100%	Yes	Resistance (15) vs Isometric (15) vs Combined (14) vs No exercise (15)	12-52 min x 3 times/ week	2.5 months

Note: (1) Studies are non-randomized Controlled Trials; (2) The study population included participants who had practiced endurance running at a competitive level for at least 40 years; (3) Exercise time includes rest breaks, i.e. 4 sets of 2-min isometric wall squat exercises interspersed with 2-min seated rest between bouts.

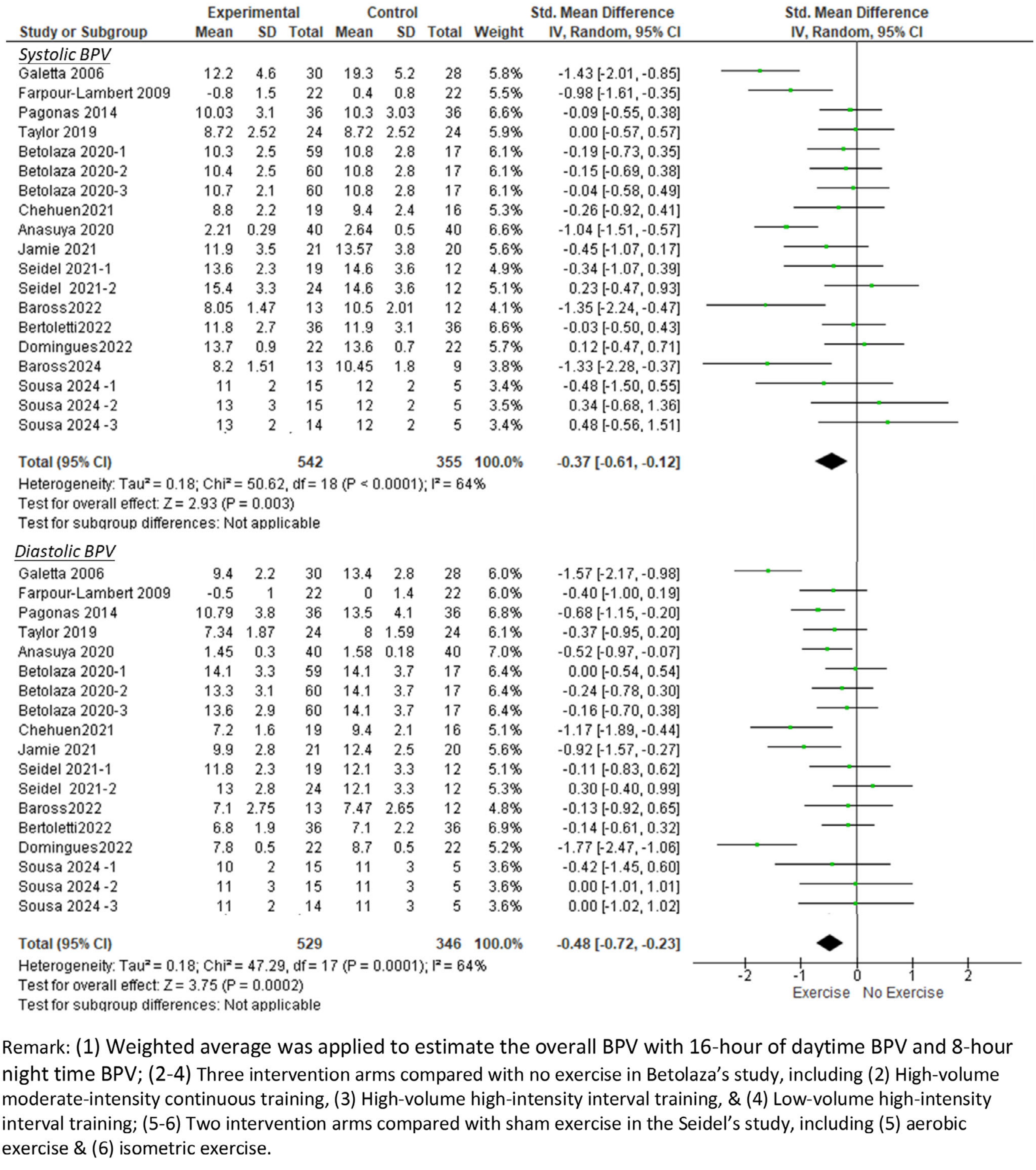

FIGURE 2 | Meta-analyses to evaluate the benefits of exercise on blood pressure variability (BPV).

was observed that aerobic exercise significantly reduces the diastolic BPV (−2.85 [−5.56, −0.07]) (Table S2).

3.5 | Sensitivity Analysis

"After excluding extremely long and short exercise durations [24, 28, 35, 36], 11 out of 15 trials (73%) indicate that exercise can reduce both systolic BPV (SMD [95% CI] = "0.28 [−0.51 to −0.05]) and diastolic BPV (SMD [95% CI] = −0.33 [−0.53 to −0.13]). Additionally, a study [25] was not conducted in adults, and there are significant differences between adolescents and adults in the diagnosis and management of hypertension. After excluding the adolescent data, 14 out of 15 trials (93%) show that exercise can marginally reduce both systolic BPV (SMD [95% CI] = −0.33 [−0.58 to −0.08]) and diastolic BPV (SMD [95% CI] = −0.48 [−0.74 to −0.22]). The result was shown to be robust

TABLE 3 | Network meta-analyses of RCTs to compare the benefits of different types of exercise on short-term BPV levels.

Exercise Types			Diastolic BPV		
Systolic BPV	Aerobic	—3.74 (−6.7, −0.74)	—2.12 (−4.37, 0.17)	—3.15 (−7.47, 1.17)	**—2.52 (−4.05, −0.99)**
	—0.77 (−3.23, 1.43)	Combined	1.62 (−0.99, 4.22)	0.59 (−3.53, 4.68)	1.21 (−1.41, 3.86)
	—0.41 (−2.29, 1.3)	0.35 (—1.61, 2.38)	Isometric	—1.02 (−5.09, 2.99)	—0.39 (−2.26, 1.42)
	—1.81 (−5.4, 1.62)	—1.03 (−4.44, 2.4)	—1.41 (−4.73, 1.93)	Resistance	—0.64 (−4.68, 3.48)
	—1.2 (−2.55, −0.02)	—0.43 (−2.42, 1.66)	—0.79 (−2.2, 0.61)	—0.62 (−3.93, 2.7)	No Exercise

Note: The table showed direct and indirect (underlined) comparisons across different types of exercise. Exercise types on the right side at a lower position were used as the reference arms, e.g. when aerobic exercise is compared with combined exercises, SMD (95% CI) for systolic BPV and diastolic BPV are −0.08 (-3.19 to 2.73) and −1.3 (-3.44 to 0.70), respectively. Bold for statistical significant findings.

3.6 | Studies With Single-Arm Comparison or Long-Term BPV

Five [39–43] single-arm studies compared the change in BPV before and after exercise interventions, including aerobic, isometric, and combined exercise (Table S4). A total of 186 participants were included, with a mean age of 57 years and 31% male. Four studies suggested three times of training per week. The duration of exercise sections ranged from 30 to 60 min. However, the meta-analysis shows that exercise did not significantly reduce either systolic BPV (SMD [95% CI] = −0.11 [−0.51 to 0.29]) or diastolic BPV (−0.12 [−0.34 to 0.09]) (Figure S6). Furthermore, another five [44–48] studies reported long-term BPV as the main outcome (Table S5). However, only one trial [45] reported full details with a control group that aerobic exercise may potentially reduce long-term systolic BPV, but its conclusion was not supported by statistical significance.

4 | Discussion

Exercise interventions effectively reduce the variability of both systolic and DBP with moderate evidence. When comparing different types of exercise, aerobic exercise is shown to be more effective for diastolic BPV. Some studies showed regular exercise over a longer follow-up period demonstrates a stronger benefit.

BPV is an important indicator associated with multiple target organ damage and a new parameter to monitor patients [49]. A recent study demonstrated that treatment with calcium channel blockers with diuretics is associated with a slight reduction in short-term BPV [50]. In addition to pharmacological treatments, incorporating regular exercise to reduce BPV can be a supportive approach to BP management. Other than exercise, a healthy diet is another potential non-pharmacological intervention to reduce BPV. A cohort study [51] of 274 participants with a mean follow-up period of 77 ± 12 months showed that a Mediterranean diet was associated with a reduction in BPV between visits ($\beta = -0.74$, $p < 0.01$). A healthy diet with an exercise intervention would help with the long-term BP variability. Therefore, reducing BP variability through a healthy lifestyle will benefit cardiovascular health [52].

The results of this study appear to differ from a previous publication [20] because this meta-analysis included more studies and focused specifically on clinical trials. The measurements of BPV, such as the CV and ARV, varied across the eligible studies, so the standardized mean difference was applied in this study to combine the results. Among the 15 included studies, 13 were RCTs, of which 3 were assessed as having some concerns and 1 as high risk of bias according to the ROB tool. The GRADE assessment for the meta-analyses evaluating the benefits of exercise on BPV was consistently rated as moderate. These findings suggest that our study provides moderate evidence and makes conclusions reliable. Still, we need more large RCTs to enhance the evidence levels. After excluding extremely long or short intervention durations and participants from the adolescent age group, the results demonstrated robustness. Although a network meta-analysis is also included, the overall interpretation remains limited due to the small number of available studies.

This meta-analysis included a reasonable sample size from 15 clinical trials; however, there are still some limitations. First, the exercise interventions were heterogeneous across the included studies, such as varying in forms of exercise, design of training modules, and follow-up duration. Therefore, a summary table was constructed to demonstrate the details of the exercise interventions (Table 2), which may provide insights for future intervention designs. Second, only about half of the eligible studies (15 out of 25) were included in the final analysis. This limitation arose because some studies were restricted by their single-arm design or focused solely on long-term BPV. Subgroup analyses were performed, but no significant findings were observed. Single-arm studies lacked a specific control group, preventing their inclusion in the network meta-analysis. Additionally, for long-term BPV, visit-to-visit blood pressure records were used; however, the definitions of these records were inconsistent, leading to their exclusion from the main findings of this study. Third, the investigation of exercise types was conducted through network meta-analysis, but the majority of studies focused primarily on aerobic exercise, with only a few addressing isometric or combined exercises. Therefore, this analysis should be updated when more literature becomes available in the coming years. Finally, some unpublished studies may not have been identified during the literature search in the OVID databases. Although the search was extended to Google Scholar, the potential for publication bias may still exist.

Exercise interventions are effective in reducing the variability of both systolic and DBP. Compared with other types of exercise, aerobic exercise is more effective for diastolic BPV. Existing clinical trials and epidemiological studies are often limited by the restricted designs of exercise training programs. Lifetime assessments of exercise levels using wearable devices will provide new insights into hypertension management.

Author Contributions

Z.H. and K.T. contribute to conceptualization. Z.H., J.T., and A.L. contribute to methodology. K.Y. contributes to software and resources. Z.H., J.T., and K.T. contribute to validation, investigation, data curation, and visualization. All authors confirmed they have contributed to the original draft writing, review, and editing. A.L., K.Y., and K.T. contribute to supervision, project administration, and funding acquisition.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data, code, and other materials can be obtained by contacting the corresponding author.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.