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Effects of Isometric Training on Heart Rate Variability: A Systematic Review and Meta-Analysis

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Abstract

Objective: To systematically review and meta-analyze the long-term effects of isometric training on heart rate variability (HRV), update previous research on isometric training's impact on HRV, explore and validate potential mechanisms and pathways underlying its blood pressure-lowering effects, and provide neurophysiological evidence for optimizing exercise prescriptions for hypertension. **Methods:** We retrieved randomized controlled trials (RCTs) on the long-term effects of isometric training on HRV from PubMed, Web of Science, CNKI, VIP, and Wanfang databases from their inception to May 8, 2025, for controlled trials examining the long-term effects of isometric training on HRV. Main effects were pooled using a random-effects model in R 4.3.3 software. **Results:** Ten studies involving 310 participants (70% hypertensive) aged 24 − 66 years were included. The meta-analysis revealed no significant differences between isometric training and non-exercise control groups in time-domain indicators (SDNN, RMSSD, pNN50) or frequency-domain indicators (LF, HF, LF/HF) of HRV ($p > 0.05$). However, marginal effects were observed for LF (Hedge’s $g = -0.26$ [-0.53, 0.01]) and LF/HF (Hedge’s $g = -0.22$ [-0.46, 0.01]) ($p < 0.1$). **Conclusion:** Isometric training has not yet demonstrated significant advantages in improving heart rate variability. However, the marginal significance of related indicators suggests that isometric training may attenuate sympathetic nervous system function by reducing LF and LF/HF, thereby reshaping autonomic nervous system balance. This offers a potential exercise intervention pathway for autonomic dysfunction caused by abnormal sympathetic activation commonly observed in hypertensive patients. Future studies should validate the potential benefits of isometric training on autonomic function through larger sample sizes, standardized intervention protocols, and long-term follow-up.

Keywords: Isometric training, Heart rate variability, Meta-analysis, Controlled trial

Introduction

Isometric training is a form of resistance training characterized by sustained muscle contraction (i.e., increased tension) without any change in the length of the involved muscle group [1]. Its remarkable efficacy in lowering blood pressure has been consistently demonstrated [2-5]. Compared to the aerobic endurance training and dynamic resistance training previously recommended by the American College of Sports Medicine [6], a recent network meta-analysis concluded that isometric training is currently the most effective exercise modality for lowering blood pressure [7]. Its high efficiency, low barrier to entry, low incidence of adverse events, and diverse implementation formats have driven extensive research and application [8-9].

Beyond its positive impact on blood pressure, studies have also examined isometric training's effects on the autonomic nervous system [10-14]. This system plays a crucial role in regulating the cardiovascular system, maintaining homeostasis through the dynamic balance of sympathetic and parasympathetic activity. Increased cardiac sympathetic activity and decreased parasympathetic activity are associated with cardiovascular events [15-16]. Heart rate variability (HRV) is currently one of the most optimal and widely applied methods for quantitatively assessing autonomic nervous system activity [17]. This non-invasive technique assesses cardiac autonomic regulation by analyzing variations in heartbeat intervals [18-19]. Previous studies attempted to elucidate the neuromodulatory mechanisms of isometric training using HRV time-domain/frequency-domain indicators. However, relevant research and meta-analyses [10,20-22] failed to identify significant HRV changes comparable to those observed in blood pressure following isometric training. However, existing evidence has clear limitations: previous meta-analyses included a small number of studies [21-22], lacked assessment of bias risk, and exhibited poor reliability of results. Therefore, this meta-analysis summarizes the long-term effects of isometric training on HRV, updates previous research on its impact, enhances methodological rigor using the Cochrane risk of bias assessment tool, and explores potential mechanisms and pathways underlying its blood pressure-lowering effects.

1 Method

1.1 Data Sources and Retrieval

Systematic searches were conducted in databases including PubMed, Web of Science, CNKI, VIP, and Wanfang. Included studies were full-text journal articles. Supplementary references were drawn from previously included studies in relevant reviews and meta-analyses. The final search date for this study was May 8, 2025. Search terms were developed based on the PICOS framework (Population, Int ervention, Comparison, Outcome): population (“adults”), intervention (“isometric training,” etc.) , comparison (“non-exercise interventions”), and outcome (“heart rate variability,” etc.).

1.2 Literature Processing and Screening

Two researchers independently performed machine and manual deduplication of retrieved literature using EndNote X9, followed by independent review of titles, abstracts, and full texts to screen the literature. A third researcher was introduced to conduct the final literature screening. In case of disagreement, the three researchers would convene a meeting to confirm inclusion/exclusion criteria and discuss until consensus was reached, after which they would review and screen the literature again.

1.3 Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were determined based on the PICOS framework. Inclusion criteria were as follows: (1) study type was a controlled trial; (2) subjects were adults aged 18 years or older ; (3) the intervention group received isometric training without additional interventions such as aerobic exercise, while the control group received non-exercise intervention or sham intervention; (4) Outcome measures included: Time-domain indicators of heart rate variability: Standard deviation of normal-to-normal RR intervals (SDNN), root mean square of successive RR interval differences (RMSSD), and proportion of successive RR intervals differing by >50 ms relative to total RR intervals. (root mean square of successive differences, RMSSD), and the proportion of successive RR interval differences >50 ms relative to total RR intervals (pNN50); Frequency domain indicators of HRV: low-frequency power (LF), high-frequency power (HF), and LF/HF ratio. Exclusion criteria were as follows: (1) Literature with inconsistent text and figure information; (2) Literature lacking complete outcome measure data; (3) Literature with total intervention duration <2 weeks.

1.4 Data Extraction and Transformation

Data extraction will be conducted independently by two researchers responsible for the screening phase. Two reviewers will independently extract participant information, isometric training protocols, and heart rate variability-related metrics from the literature. A third researcher will perform a round of checks. In case of disagreement, the three reviewers will self-check and reconvene until a final consensus is reached. For missing data or data presented only graphically, authors will first be contacted to request the information. If contact fails and corresponding graphs are available, data will be extracted using GetData Graph Digitizer.

If the study provides standard errors (SE), convert them to standard deviations (SD) [23]:：

$$SD = \sqrt{N} \times SE \quad (1)$$

When comparing the difference in change values between the intervention group and the control group, use the following formula to calculate the mean difference:

$$Mchange = Mpost - Mpre \quad (2)$$

Mpost represents the post-test mean scores for both the intervention and control groups; Mpre denotes the pre-test mean scores for both groups. The change in SD for each group is calculated using the following formula：

$$SDchange = SDpre2 + SDpost2 - (2 \times R \times SDpre \times SDpost) \quad (3)$$

SDpre denotes the pretest standard deviation for both the intervention and control groups; SDpost denotes the posttest standard deviation for both groups; R represents the correlation coefficient between pretest and posttest scores. Following recommendations in the Cochrane Handbook [24], R is set to 0.5 in this study.

The formula for combining subgroups is as follows:

Assume subgroup A has a sample size N1, mean M1, and standard deviation SD1; Subgroup B has a sample size of N2, mean of M2, and standard deviation of SD2. The combined sample size N is N = N1 + N2, and the combined mean M is calculated as M = (N1M1 + N2M2) / (N1 + N2). The formula for the combined standard deviation is：

$$SD = \sqrt{\frac{(N_1 - 1)SD_1^2 + (N_2 - 1)SD_2^2 + \frac{N_1 N_2}{N_1 + N_2}(M_1^2 + M_2^2 - 2M_1 M_2)}{N_1 + N_2 - 1}} \quad (4)$$

1.5 Assessment of Bias Risk

Risk of bias was assessed independently by two researchers. Disagreements were resolved through discussion; if unresolved, a third researcher served as arbitrator. The Cochrane Collaboration's Risk of Bias 2 tool was used for assessment, evaluating risk of bias across the following domains: randomization process, deviation from the specified intervention, missing outcome data, outcome measurement, and selective reporting of results [25].

1.6 Statistical Methods

This meta-analysis employed the inverse variance method based on the DerSimonian-Laird approach [26] and used a random-effects model for combining main effects. The Jackson method was applied to calculate tau^2, tau, and their confidence intervals [26]. Mean values, standardized mean differences (SMD), mean differences (MD), and 95% confidence intervals (95% CI) were extracted from individual studies to calculate the pooled main effect. Effect sizes were expressed as Hedge's g, categorized as follows: 0.2 indicates a small effect, 0.5 indicates a moderate effect, and 0.8 indicates a large effect [27]. This study defines I^2 as follows: low heterogeneity: 0%-30%; moderate heterogeneity: 30%-50%; high heterogeneity: 50%-75%; very high heterogeneity: 75%-100%[28]. To assess the robustness of meta-analysis results and the potential impact of individual studies on the pooled effect size, sensitivity analysis was conducted using the leave-one-out method. From the original included studies, one study was sequentially excluded at a time. The pooled effect size and its 95% confidence interval were rec alculated based on the remaining studies. The magnitude of change in the effect size and whether the statistical significance underwent substantive alteration after excluding each study were compared. Publication bias was assessed using funnel plots combined with Egger's test [29-30], with $p > 0.05$ indicating no risk of publication bias. Statistical analyses and graphing were performed using the "meta" and "metafor" packages in R software (version 4.3.3). Statistical significance was set at $p < 0.05$.

2 Result

2.1 Literature Search Results

Preliminary searches across databases yielded a total of 1,068 articles, with 10 studies ultimately included in the meta-analysis. The workflow and corresponding screening results are shown in Figure 1

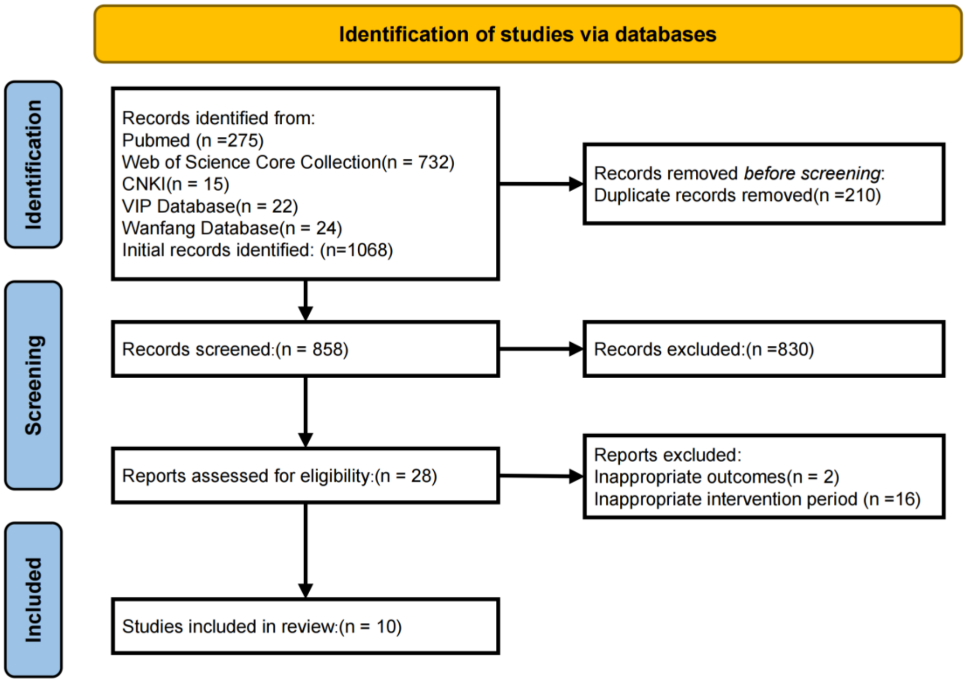

Figure 1. Flow Chart of Literature Retrieval

2.2 Included in the literature characteristics

This review included 10 studies (9 randomized controlled trials), with sample sizes ranging from 17 to 102 participants per study. A total of 310 participants were included, with an average age range of 24－66 years. Participants' health statuses were categorized as healthy (42 participants, 14%), hypertensive (198 participants, 64%), and peripheral arterial disease (70 participants, 23%); Weight categories included normal weight (22 participants, 9%), overweight (113 participants, 49%), and obese (97 participants, 42%). Intervention durations ranged from 4 to 12 weeks. Isometric exercise modalities comprised isometric grip strength training (266 participants, 86%) and wall sit (44 participants, 14%).

Table 1. The Basic Information of the Included Literatures

	Subject Information			Isometric Training Program				
Author	**Sample size**	**Age**	**Weight, Health Status**	**Intervention Cycle**	**Intervention frequency**	**Type**	**Interval**	**Outcome Indicator**
Badrov et al.2013[10]	22	24	Normal, healthy	weeks	3 to 5 times per week	Isometric Grip Strength	4min	①②③④⑤⑥
Correia et al. 2020[31]	70	66	Overweight, peripheral artery disease	weeks	3 times a week	Isometric Grip Strength	4min	①②③⑥
Decaux et al. 2022[32]	20	30	Overweight, Health	weeks	3 times a week	Wall squat	2min	④⑤⑥
Farah et al. 2018[11]	48	59	Obesity, hypertension	weeks	3 times a week	Isometric Grip Strength	1min	①②③④⑤⑥
Javidi et al.2022[33]	39	46	NA、Hypertension	8weeks	3 to 5 times per week	Isometric Grip Strength	4min	①③④⑤⑥
Millar et al.2013[12]	23	65	Overweight, Hypertension	weeks	3 times a week	Isometric Grip Strength	4min	①②③④⑤⑥

Palmeira et al. 2021[34]	31	53	Obesity, hypertension	weeks	3 times a week	Isometric Grip Strength	1min	①②③④⑤⑥
Stiller-Moldovan et al. 2012[13]	18	61	Obesity, hypertension	weeks	3 times a week	Isometric Grip Strength	1min	⑥
Taylor et al.2003[14]	15	66	NA、Hypertension	weeks	3 times a week	Isometric Grip Strength	1min	⑥
Taylor et al.2019[35]	24	44	NA、Hypertension	weeks	3 times a week	Wall squat	2min	④⑤⑥

Note：NA：Not Applicable.①SDNN②RMSSD③pNN50④LF⑤HF⑥LF/HF

2.3 Literature Bias Risk Assessment Results

The risk of bias in the included studies was concentrated in the randomization process,deviation from the specified intervention, and outcome measurement, all of which may carry a certain risk of bias.

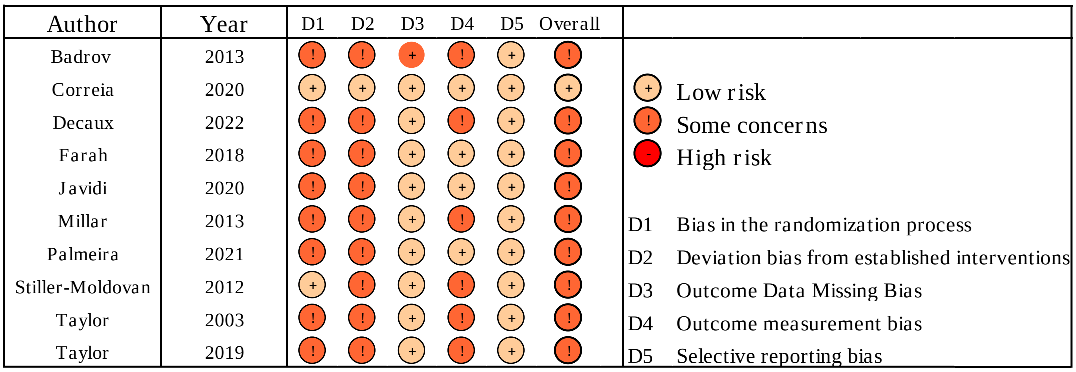

Figure 2. The Risk Assessment of Bias in the Included Literature

2.4 Meta-analysis results

2.4.1 Time-domain indicators

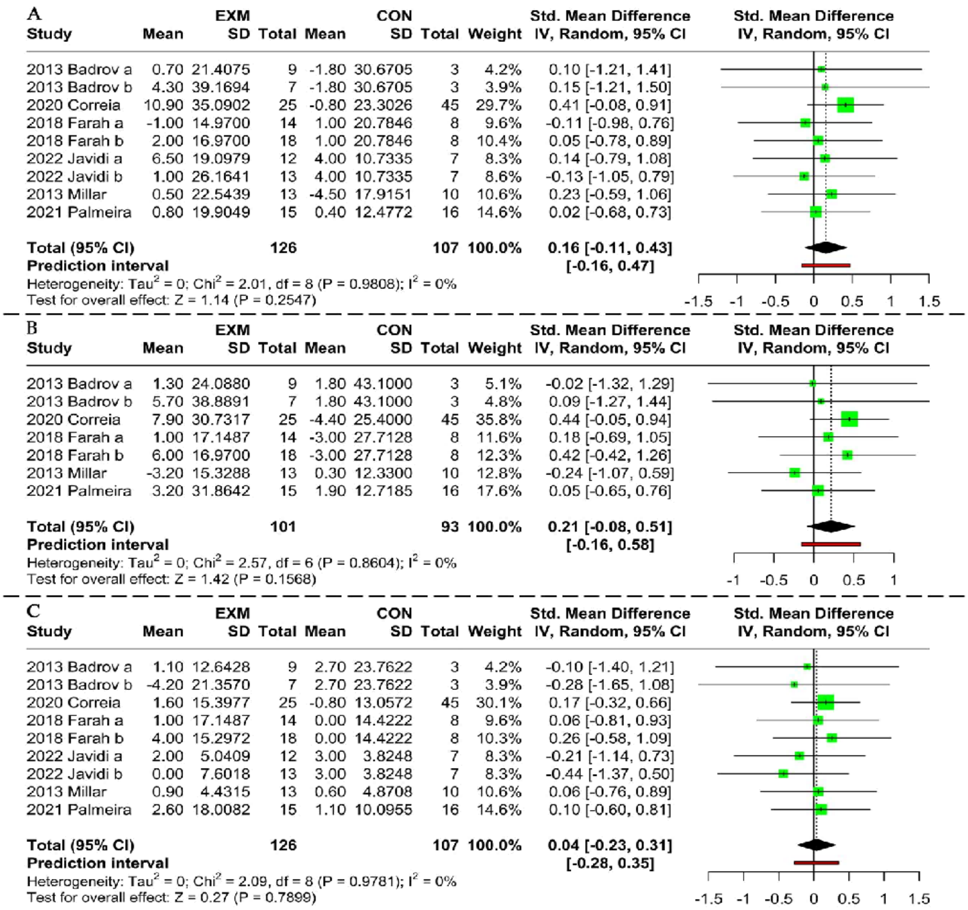

Figure 3. Meta-analysis results of time-domain analysis indicators

Note：A：SDNN；B：RMSSD；C：pNN50

The meta-analysis results for time-domain indicators indicated no significant differences between isometric training and the control group regarding the effects on SDNN (p=0.25), RMSSD (p=0.16), and pNN50 (p=0.79). The standardized mean differences and their 95% confidence intervals were as follows: SDNN: SMD = 0.16 (95% CI: -0.11, 0.43); ; RMSSD: SMD = 0.21 (95% CI: -0.08, 0.51); pNN50: SMD = 0.04 (95% CI: -0.23, 0.31). The pooled results exhibited low heterogeneity (I^2 = 0%). Sensitivity analyses confirmed the stability of the pooled results.

2.4.2 Frequency domain indicators

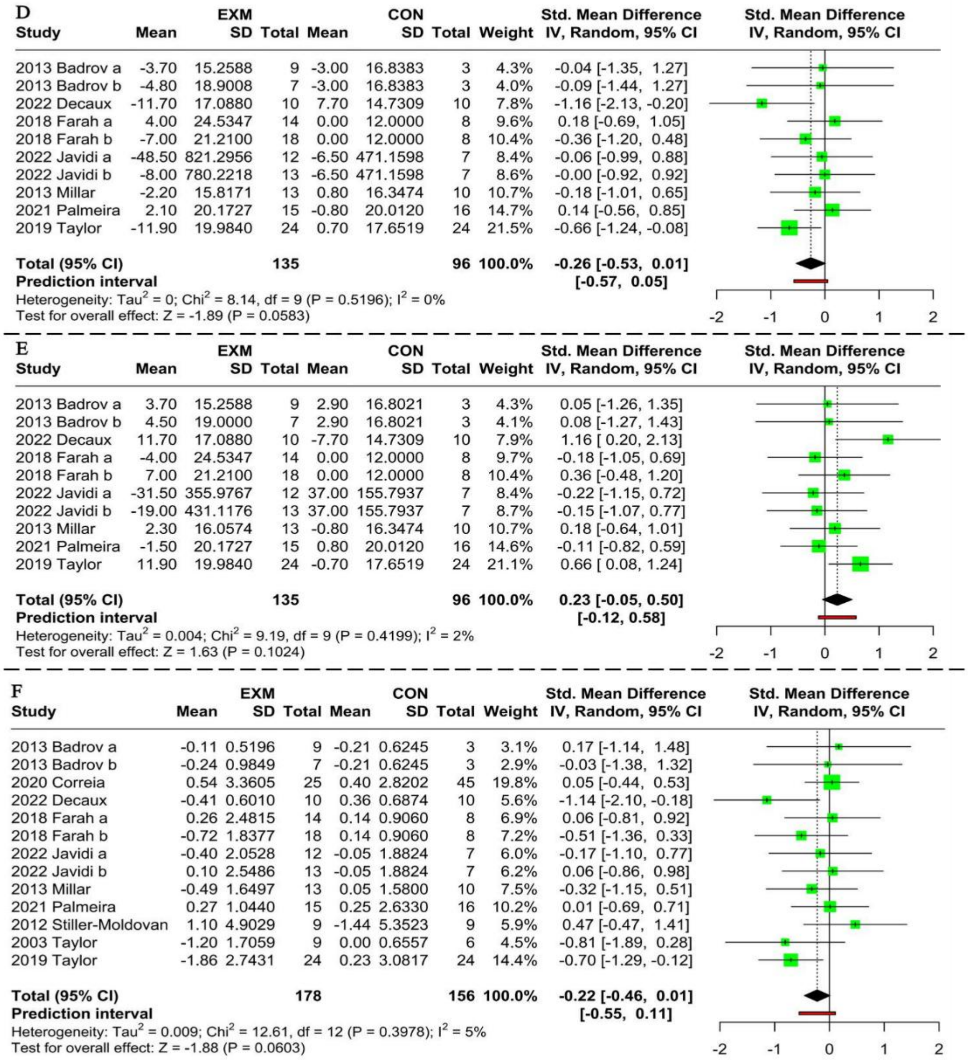

Figure 4. Meta-analysis results of time-domain analysis indicators

Note：D：LF；E：HF；F：LF/HF

Meta-analysis results for frequency domain indicators indicate that isometric training showed no significant differences compared to the control group in LF (p=0.06), HF (p=0.10), and LF/HF (p=0.06). However, LF (Hedge’s g=-0.26 [-0.53, 0.01]) and LF/HF (Hedge’s g = -0.22 [-0.46, 0.01]) showed borderline significant effects ($p < 0.1$). Heterogeneity in pooled results was low (I^2 = 0%, 2%, and 5%, respectively), and sensitivity analyses confirmed stable pooled results.

2.5 Risk of Publication Bias

Based on Egger's test, the combined results of the main effects for SDNN (p=0.08), RMSSD (p=0.20), pNN50 (p=0.06), LF (p=0.53), HF (p=0.92), and LF/HF (p=0.46) may not be at risk for publication bias.

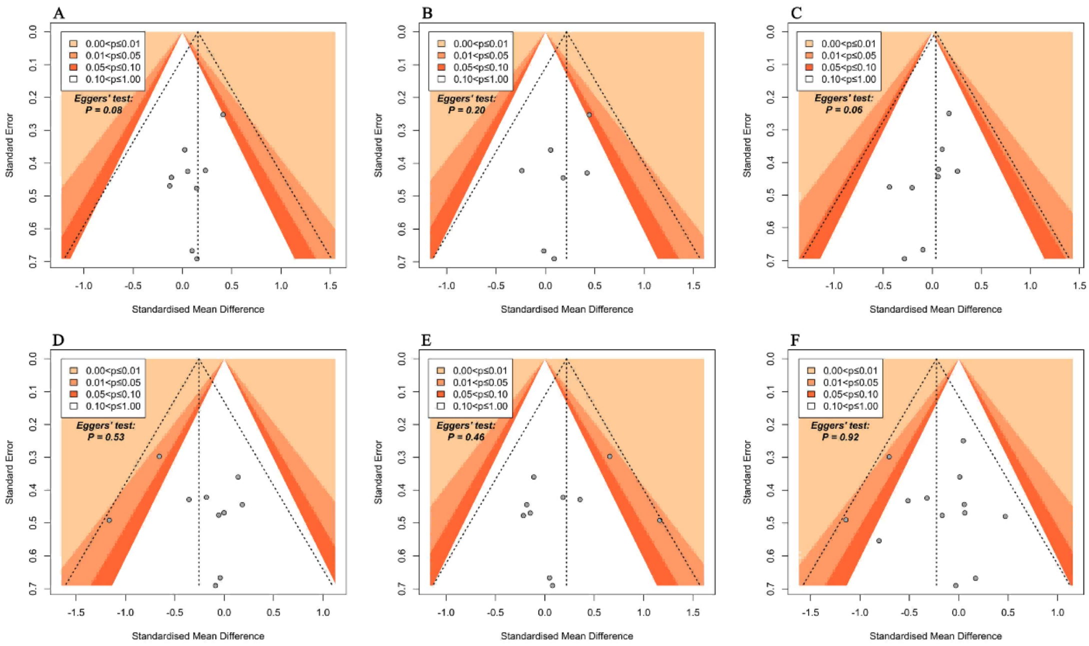

Figure 5. Publishing Bias Funnel Plots

Note：A.SDNN；B.RMSSD；C.pNN50；D.LF；E.HF；F.LF/HF；

3 Discussion

The autonomic nervous system primarily consists of the sympathetic and parasympathetic nervous systems, which maintain stability through mutual balance. Hypertensive patients exhibit autonomic dysfunction, with the predominant developmental mechanism widely recognized as autonomic imbalance—manifesting as abnormal sympathetic activation [36] and weakened parasympathetic function. Consequently, current therapeutic approaches for rebalancing the autonomic nervous system in hypertensive patients primarily focus on two aspects: reducing sympathetic activity and enhancing parasympathetic function [37].

3.1 Effects of Isometric Training on Time-Domain Indicators

SDNN reflects overall autonomic nervous system activity, with elevated values indicating increased parasympathetic activity; RMSSD reflects parasympathetic activity, with elevated values indicating increased parasympathetic activity [17]. SDNN < 70 ms has been demonstrated as an independent risk factor for cardiovascular mortality. A meta-analysis revealed that compared to cardiovascular disease patients with high HRV, those with low HRV exhibited a 121% increased risk of all-cause mortality and a 46% increased risk of cardiovascular events [33]. SDNN, RMSSD, and pNN50 negatively correla te with the Gensini score for coronary artery lesions [39]. Improvements in time-domain indicators ne gatively correlate with cardiovascular factors such as arrhythmia, heart failure, and coronary artery dis ease [17]. Research findings indicate that although effect estimates suggest positive trends in time-do main HRV indicators following isometric training, improvements in SDNN, RMSSD, and pNN50 wer e not statistically significant ($p > 0.05$).

3.2 Effects of Isometric Training on Frequency Domain Indicators

LF reflects the synergistic interaction between the sympathetic and parasympathetic nervous syst ems, though sympathetic dominance prevails. Elevated LF indicates increased sympathetic nervous sy stem activity. HF reflects parasympathetic nervous system activity; elevated HF indicates increased pa rasympathetic nervous system activity. The LF/HF ratio represents the balance between sympathetic a nd parasympathetic nervous systems, with an elevated ratio indicating predominant sympathetic nervo us system activity [37][40]. Hypertensive patients commonly exhibit lower HF [41] and higher LF and LF/HF ratios. A 4-week isometric intervention significantly reduced normalized LF (in %) and increa sed normalized HF in physically inactive individuals, though absolute LF (in ms^2) and HF showed no significant difference compared to the control group [32]. suggesting that the choice of measurement u nits may influence the interpretation of final conclusions. Improvements in HRV observed after isomet ric training in non-hypertensive populations also indicate the universality of isometric training in enha ncing autonomic nervous function. Taylor et al.[35] noted that supervised isometric grip training signif icantly improved LF in uncontrolled hypertensive patients. Collectively, these findings may suggest th at isometric grip training can improve cardiovascular parameters in patients with poorly controlled blo od pressure.

The present study found that isometric training did not significantly affect the frequency domain i ndicators of HRV (LF, HF, and LF/HF). However, a trend toward improvement in LF and LF/HF was observed, showing borderline significance ($0.05 < p < 0.1$). To some extent, this suggests that isometri c training may improve certain aspects of HRV. The effects on the autonomic nervous system primaril y manifest as a reduction in sympathetic function. There is also a possibility of enhanced parasympath etic activity through improved HF (Hedge’s g=0.23 [-0.05,0.50], p=0.1). Future studies are needed to further investigate HRV changes following isometric training.

4 Research Limitations

This study focused solely on the long-term effects of isometric training on heart rate variability th rough experimental interventions, without examining its short-term impact on heart rate variability. Th e intervention periods across included studies varied considerably (4 to 12 weeks), which may have inf luenced the observed effects on blood pressure reduction. Furthermore, some included studies did not f ully report participants' baseline characteristics (such as gender and BMI), limiting the feasibility of co nducting subgroup analyses in subsequent research.

5 Conclusion

Isometric training did not significantly affect SDNN, RMSSD, or pNN50 in the time-domain indicators of heart rate variability (HRV). However, it showed a trend toward improvement in the frequency-domain parameters LF and LF/HF ($0.05 < p < 0.1$). Although the effect estimates indicated a trend toward improvement in HRV-related parameters with isometric training, their confidence intervals spanned zero, suggesting insufficient evidence to support statistical significance. This finding may be constrained by the small sample sizes of included studies or variability in measurement methods. Future research should validate the potential benefits of isometric training on autonomic nervous system function through larger samples, standardized intervention protocols, and long-term follow-up.

Disclosure

Author Contributions: Conceptualization:XiongZhuang Xu; methodology: XiongZhuang XU; check: Li Peng; datacuration: XiongZhuang Xu; supervision: Li Peng

Authors have read and agreed with the published version of the manuscript.

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