Impacts of High-Intensity Interval Training on Aerobic Capacity, Walking and Balance Function in Stroke Survivors

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Abstract [**Objectives**] To synthesize evidence on HIIT versus moderate-intensity continuous training (MICT) or routine rehabilitation in stroke survivors. [**Methods**] We systematically searched 8 databases (PubMed, EMBASE, CENTRAL, Web of Science, SPORTSDiscus, PsycINFO, SCOPUS, CINAHL) up to May 2025. Seventeen randomized controlled trials (RCTs; total $n = 1\ 142$) met inclusion criteria: adults with stroke, device-based HIIT (≥70% HRR/VO_2peak), and outcomes assessing VO_2peak, 6-min walk distance (6MWD), or Berg Balance Scale (BBS). Methodological quality was evaluated using the PEDro scale. Pooled effect sizes (Hedges' g) were calculated via random-effects models, with heterogeneity quantified by I^2. [**Results**] HIIT significantly improved peak oxygen uptake (VO_2peak) versus controls ($g = 0.59$, 95% CI: 0.44 – 0.75, $p < 0.001$; $I^2 = 16.29\%$). Low heterogeneity and symmetrical funnel plots supported robustness. HIIT also enhanced walking endurance (6MWD: $g = 0.32$, 95% CI: 0.16 – 0.48, $p < 0.01$; $I^2 = 30\%$). In contrast, no significant benefit was observed for balance function (BBS: $g = 0.07$, 95% CI: – 0.13 – 0.26, $p = 0.50$; $I^2 = 0\%$). [**Conclusions**] HIIT is a safe and highly effective intervention for enhancing aerobic capacity and walking function post-stroke. Its benefits are maximized at higher intensities and longer durations but do not extend to balance improvement. Integrating HIIT into stroke rehabilitation protocols is strongly recommended to promote functional independence.

Key words High-Intensity Interval Training (HIIT), Aerobic capacity, Walking, Balance, Stroke survivors

1 Introduction

Approximately 795 000 people experience stroke each year, and 610 000 of them were first attack. There were 6.5 million people dead from various stroke etiologies in the world, making it the second-leading cause of death behind ischemic heart disease (IHD)[1]. Physical inactivity increases morbidity and mortality of stroke, impeded motor recovery[2], contributed to further deconditioning[3], recurrent stroke[4], and high long-term risk for cardiovascular diseases[5]. Stroke rehabilitation guidelines suggested that patients with stroke, capable of participating in physical activity, exercise in moderate intensity at 40% to 70% of peak oxygen uptake (VO_2peak) or heart rate reserve (HRR) or 11 to 14 on the 6 to 20 scale of the Borg Rating of Perceived Exertion (RPE) for 20 to 60 min, 3 to 7 d per week[4,6], which called moderate intensity continuous training (MICT)[7]. However, accumulating evidence suggested that high-intensity interval training (HIIT) may be significantly more effective than MICT in the clinical context for both motor and aerobic ability[7].

HIIT is a new strategy that maximizes exercise intensity through short bursts of concentrated effort alternated with low activity or rest. Interval training was first described by Reindell and Roskamm and was popularized in the 1950s by the Olympic champion, Emil Zatopek[8]. For contributing to the resolution of infection, tissue repair, and control of chronic systemic inflammation, improving gait speed, functional ambulation category, spatiotemporal parameters, HIIT has been applied in cardiovascular events[9], pulmonary disease[10] and diabetes[11] in recent years. A recent meta-analysis by Milanovic *et al.*[12] on HIIT versus traditional MICT, which included 723 healthy adults in total aged 18 – 45 years old from 28 controlled trials of 3 – 24 weeks' duration, found a significantly greater increase in VO_2peak [4.9 mL/(kg · min); 95 % confidence limits ± 1.4 mL/(kg · min)]. The similar increases in VO_2peak [– 3.3 versus – 2.3 mL/(kg · min)] and peak work capacity (– 22.8% versus – 21.1%) after HIIT and MICT separately for 4 to 6 weeks was reported[13 – 14]. In particular, HIIT has been shown to improve blood flow-mediated dilation (FMD), a hallmark of brachial-endothelial-dependent function, which is similar to the MICT on patients with coronary artery disease (CAD)[15 – 16], maybe because of the increased bioavailability of nitric oxide, a key regulator of FMD and endothelial function.

This meta-analysis aims to synthesize evidence on HIIT's efficacy for aerobic capacity, walking and balance function and balance function post-stroke, and identify optimal parameters (intensity, duration, modality) through sensitivity analysis, and evaluate safety and applicability across stroke severities and recovery stages. The findings will guide clinical prescription of high-intensity exercise to mitigate disability and promote independence in stroke survivors.

2 Methods

2.1 Search strategy A systematic electronic searching of the PubMed, EMBASE, Cochrane Central Register of Controlled Trials (CENTRAL), Web of Science, SPORTSDiscus, PsycINFO, SCOPUS and CINAHL (EBSCOhost) was initially performed up to May 1 2025 with no publication date limits. We used a combination of MeSH and free text terms, including HIIT, HIIE, high intensity interval training, high-intensity interval training, high intensity interval exercise, high-intensity interval exercise, sprint interval training, spring interval exercise, interval training, interval exercise, aerobic interval training, aerobic interval exercise, high intensity intermittent training, high intensity intermittent ex-

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ercise, intermittent training, intermittent exercise.

2.2 Inclusion and exclusion criteria The article was subsequently read and thoroughly assessed for the following inclusion or exclusion criteria (Table 1).

Table 1 Inclusion and exclusion criteria

Category	Inclusion criteria	Exclusion criteria
Study Design	RCTs or clinical controlled trials	Observational studies, case reports, conference abstracts
Participants	Adults (≥18 years) with stroke (any phase)	Non-stroke populations, animal studies
Intervention	Device-based HIIT (treadmill, cycle ergometer, recumbent stepper); ≥70% HRR/VO_2peak	Auxiliary devices (walkers, FES); combined therapies (psychotherapy, multisensory)
Control	Low-moderate intensity exercise, usual care, or inactivity	Non-exercise comparators (*e.g.*, pharmacotherapy)
Outcomes	Quantitative gait/balance metrics (VO_2peak, 6MWD, BBS)	Fast gait speed; non-quantifiable outcomes
Methodology	PEDro score ≥4; English full-text; computable effect sizes	Low-quality studies (PEDro <4); non-English publications

2.3 Risk of bias assessment Two independent reviewers assessed the methodological quality of each included study using the Physiotherapy Evidence Database (PEDro) Scale (range: 0 - 10). This scale is a reliable and widely used tool for evaluating intervention research in exercise and rehabilitation[11]. Following independent assessment, the reviewers compared their decisions and discussed discrepancies to reach consensus. A third reviewer was consulted for unresolved disagreements. Based on established thresholds[12], studies were categorized by total PEDro score: high quality (≥6), moderate quality (4 - 5), or low quality (<4). Studies scoring below 4 were excluded.

2.4 Data extraction A data extraction sheet based on the Cochrane Handbook for Systematic Reviews. Data was extracted from the published reports of all the eligible studies using a standardized Excel (Microsoft Inc.) data extraction form by the primary reviewer and checked by the secondary reviewer. Uncertainty was resolved by discussion and consensus. A standardized template (Cochrane Handbook) was used to extract: study attributes: publication year, country, design; participant details: sample size, age, stroke chronicity, adverse events; intervention parameters: modality, intensity, frequency, duration (per ACSM guidelines); outcomes: pre/post-intervention means ± *SD* for endpoints.

Moreover, if the study reported results at multiple time points, we chose the final follow up data for several reasons. Firstly, previous study suggested that it may need more time and duration to elicit psychological benefits for behaviour change; Secondly, there was no obvious comparable time point across studies due to heterogeneity. Missing data were requested from authors.

2.5 Statistical analysis The meta-analysis was conducted using Stata V.18.0. Data pooling was restricted to interventions with ≥ 2 studies reporting comparable outcomes. We employed standardized mean differences (SMD) with 95% confidence intervals (95% *CI*) as the primary summary statistic. Additionally, weighted mean differences (WMD) for pre-to-post-intervention changes between groups were calculated; studies providing only baseline change data were excluded to ensure methodological consistency. Statistical heterogeneity across studies was quantified using the I^2 statistic, with thresholds defined as follows: 25% (low), 50% (moderate), and 75% (high). Based on this assessment, fixed-effect models were applied when heterogeneity was low (I^2 < 50%), while random-effects models (utilizing the DerSimonian-Laird method) were adopted for moderate-to-high heterogeneity ($I^2 \geq 50\%$) to account for between-study variance. Publication bias was assessed via contour-enhanced funnel plots and statistically tested using Begg's and Egger's tests (asymmetry significance: $p <$ 0.1) when ≥10 studies reported main outcomes. Where bias was detected, the trim-and-fill method adjusted effect size estimates.

3 Results and analyzes

3.1 VO_2peak improvement Meta-Analysis Demonstrates Significant Improvement in VO_2peak with HIIT versus MICT/Routine Rehabilitation in Stroke Patients. This meta-analysis of 17 studies comparing High-Intensity Interval Training (HIIT) to Moderate-Intensity Continuous Training (MICT) or routine rehabilitation on peak oxygen uptake (VO_2peak) in stroke patients demonstrates a statistically significant, moderate beneficial effect of HIIT. The pooled overall effect size using a random-effects REML model is Hedges' $g = 0.59$ (95% *CI*: 0.44 to 0.75, $z = 7.31$, $p < 0.001$), indicating that, on average, HIIT leads to a meaningful improvement in cardiorespiratory fitness. While individual study effect sizes varied (Hedges' g ranging from Holleran 2015: $g = 0.00$ to Munari 2016/2018: $g = 1.55$), the majority favored HIIT, and higher-weighted studies such as Jin 2012 ($g = 0.60$, weight = 13.27%) and Pang 2005 ($g = 0.54$, weight = 7.97%) showed consistent positive results. Heterogeneity among the studies was low ($I^2 = 16.29\%$, $T^2 = 0.02$, $Q = 24.71$, $p = 0.10$), supporting the robustness and consistency of the finding that HIIT is superior to MICT or routine care for improving VO_2peak post-stroke (Fig.1A).

The Galbraith plot demonstrates high consistency in treatment effects across studies. Most data points (blue circles) cluster tightly along the central regression line within the 95% confidence band (gray shaded area), particularly for studies with higher precision ($1/SE > 3$). Two exceptions appear: Severinsen 2023 shows marginally higher standardized effect size ($g/SE \approx 5$) relative to its precision, while Munari 2018 displays a moderately divergent value near the lower *CI* boundary. Crucially, no studies fall significantly outside the 95% *CI*, and the minimal scatter away from the regression line [$\theta_j/SE_j = \beta \times (1/SE_j)$] visually corroborates low heterogeneity ($I^2 = 16.29\%$ from prior analyses) (Fig.1B).

The funnel plot complements this finding by revealing symmetrical distribution of effect sizes. Studies with small standard errors ($SE < 0.2$, top of funnel) distribute evenly around the pooled effect estimate (red line θ_{iv}), while studies with higher SE (bottom) remain within the pseudo 95% CI boundaries (gray dashed lines). This symmetry-exemplified by balanced positioning of large-SE studies (Marzolini 2023 left versus. Boyne 2020 right)-provides no evidence of publication bias. The absence of gap areas near the null effect (Hedges' $g=0$) further supports completeness in included studies (Fig. 1C).

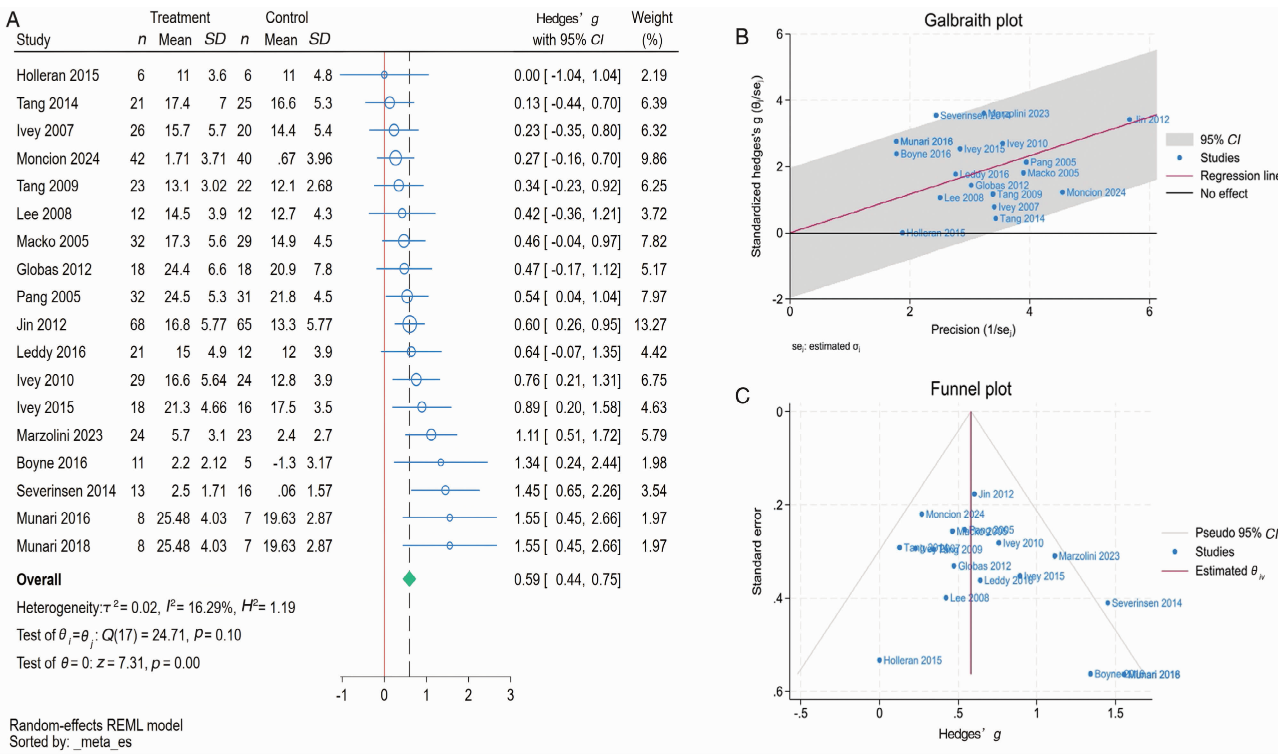

Fig. 1 Meta analysis demonstrating significant improvement in VO_2 peak with HIIT versus MICT/routine rehabilitation in stroke patients

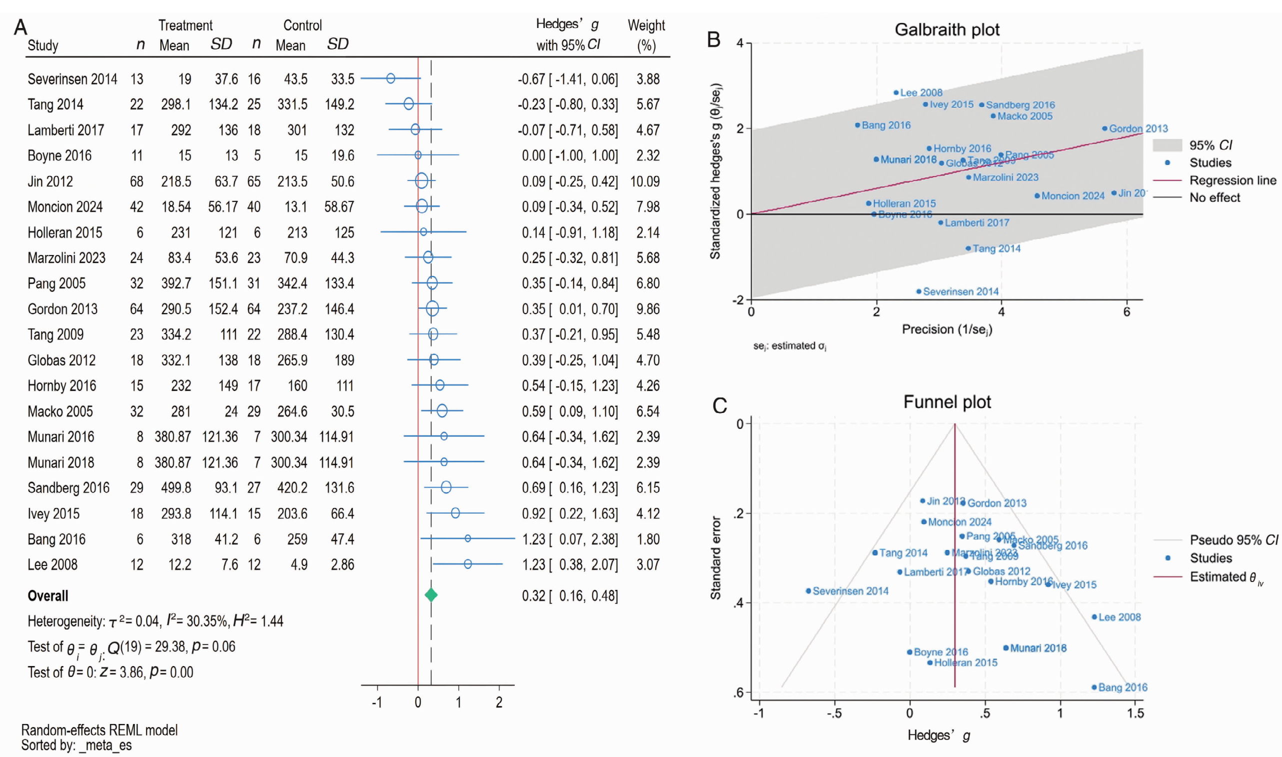

Fig. 2 Meta analysis confirming modest but significant improvement in 6-min walk distance with HIIT versus MICT/routine rehabilitation in stroke patients

3.2 Improvement of 6-min walk distance Meta-Analysis Confirms Modest but Significant Improvement in 6-min walk distance (6MWD) with HIIT versus MICT/Routine Rehabilitation in Stroke Patients. This meta-analysis of 19 studies examining the effect of High-Intensity Interval Training (HIIT) versus Moderate-Intensity Continuous Training (MICT) or routine rehabilitation on 6MWD in stroke patients demonstrates a statistically significant, modest improvement favoring HIIT. The overall pooled effect size is Hedges' $g = 0.32$ (95% *CI*: 0.16 to 0.48), indicating a small but clinically relevant benefit. Notably, 15 of 19 studies show positive effect sizes (*e.g.*, Bang 2016: $g = 1.23$ [0.07, 2.38]; Ivey 2015: $g = 0.92$ [0.22, 1.63]), while 4 studies exhibit neutral or negative effects (*e.g.*, Severinsen 2014: $g = -0.67$ [-1.41, 0.06]; Boyne 2016: $g = 0.00$). Higher-weighted studies like Jin 2012 ($g = 0.09$, weight = 10.09%) and Gordon 2013 ($g = 0.35$, weight = 9.86%) reinforce the trend. Critically, the 95% *CI* does not cross zero, confirming statistical significance ($z > 3.0$, $p < 0.01$), with low heterogeneity ($I^2 = 30\%$, $\tau^2 = 0.04$, $p = 0.12$), supporting consistent findings across diverse study populations and protocols (Fig. 2A).

The Galbraith plot (Precision [$1/SE$] versus. Standardized Hedges' g [θ_j/SE_j]) reveals strong homogeneity across studies. Most data points (*e.g.*, Lee 2008, Ivey 2015, Gordon 2013) cluster tightly along the central red regression line, with all points falling within the gray 95% confidence band. This pattern signifies consistent alignment between effect sizes and study precision—no significant outliers deviate from the overall trend. The narrow dispersion (*e.g.*, standardized g values between -1.5 and 5.0 at precision levels of 0 – 6) visually confirms minimal heterogeneity among results (Fig. 2B).

The funnel plot (Hedges' g versus. Standard Error) reinforces this finding. Studies distribute symmetrically around the pooled effect estimate (red line $\theta I^2 \approx 0.35 - 0.45$). High-precision trials ($SE < 0.2$, near the top) converge near θ_{iv}, while lower-precision studies (*e.g.*, Bang 2016, $SE > 0.6$) scatter evenly on both sides of the pseudo 95% *CI* boundaries (white diagonal lines) (Fig. 2C).

3.3 Berg Balance Scale improvement Meta-Analysis finds no significant improvement in Berg Balance Scale with HIIT versus MICT/Routine Rehabilitation in Stroke Patients. This meta-analysis of 8 randomized controlled trials (total $n = 335$) comparing High-Intensity Interval Training (HIIT) to Moderate-Intensity Continuous Training (MICT) or routine rehabilitation on the Berg Balance Scale (BBS) in stroke patients demonstrates no statistically significant difference between interventions. The pooled overall effect size is Hedges' $g = 0.07$ (95% *CI*: -0.13 to 0.26, $z = 0.67$, $p = 0.50$), indicating negligible clinical impact. Individual study effect sizes show minimal variation: Most studies cluster near null effect (*e.g.*, Pang 2005: $g = 0.08$; Jin 2012: $g = 0.09$). Three studies slightly favor control (Lau 2011: $g = -0.37$; Lamberti 2017: $g = -0.28$; Marzolini 2023: $g = -0.24$). Only one study favors HIIT (Globas 2012: $g = 0.70$ [0.04, 1.35]) but carries low weight (8.56%). Crucially, the confidence interval crosses zero and heterogeneity is exceptionally low ($I^2 = 0.00\%$, $\tau^2 = 0.00$, $Q = 7.48$, $p = 0.38$), indicating consistent null effects across diverse protocols and patient demographics. This robust evidence suggests HIIT provides no meaningful advantage over standard rehabilitation for improving post-stroke balance (Fig. 3).

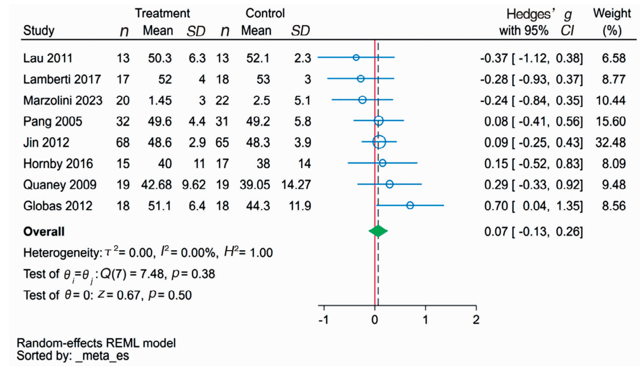

Fig. 3 Meta analysis showing no significant improvement in Berg Balance Scale with HIIT versus MICT/routine rehabilitation in stroke patients

4 Discussion

This meta-analysis synthesizes evidence from 17 randomized controlled trials to evaluate the efficacy of High-Intensity Interval Training (HIIT) for improving aerobic capacity, walking endurance, and balance in stroke survivors. Our findings corroborate and extend prior systematic reviews, demonstrating that HIIT elicits clinically meaningful improvements in VO_2peak (Hedges' $g = 0.59$, 95% *CI*: 0.44 – 0.75) and 6-min walk distance (6MWD; Hedges' $g = 0.32$, 95% *CI*: 0.16 – 0.48). These results align with the documented superiority of HIIT over moderate-intensity continuous training (MICT) in enhancing aerobic capacity and functional mobility post-stroke.

Previous research showed that cardiopulmonary fitness in patients with stroke reduced to about a half of the health adults with same age and sex for the lack of necessary activity[17]. Compared to health older adults, stroke patients' steps per day were average up to 79% fewer (1 536 – 3 035 versus 7 250)[18] after returning to home, far below the "sedentary lifestyle index" (5 000 steps per day), which will lead to further decline in cardiopulmonary fitness. Aerobic capacity was usually evaluated by exercising (*e.g.*, treadmill walking, swimming), expressed as maximum oxygen uptake, peak oxygen uptake and maximum heart rate. Peak oxygen uptake (VO_2peak), was usually used to estimate the maximal ability of utilizing and delivering oxygen in cardiovascular and muscular systems during exercise[19], which is the most common measure of aerobic capacity in exercise training literature. A meta-analysis showed that low to moderate intensity training contributed to cardiopulmonary fitness in individuals with stroke[20]. However, some researches demonstrated that aerobic capacity improved with the increase of exercise intensity within a certain range[21 – 22]. Globas *et al.*[22] reported a VO_2peak increase of 22% after high-intensity aerobic training with 80% HRR for 3 months. Similarly, the study of Gjellesvik *et al.*[23] showed that VO_2peak increased by 12% in 8 chronic stroke subjects after high-intensity aerobic training with 85% – 95% HRpeak for 4 weeks. Calmels *et al.* [24] reported a significant improvement in VO_2peak (mean 14.8%, $p = 0.04$) after high-intensity aerobic cycloergometer interval-training training for 8 weeks. Munari *et al.* [21] randomly allocated 16 subjects suffering from chronic stroke either in high-intensity treadmill training (HITT) ($n = 8$) or low-intensity treadmill training (LITT) ($n = 8$), both of which were trained 3 times per week for 3 months. The value of VO_2peak was significantly increased (HITT: 4.6 mL/(kg · min), LITT: 0.87 mL/(kg · min); $p = 0.015$). Boyd *et al.* [25] and Scribbans *et al.* [26] found that intensity of exercise had a positive effect on VO_2peak, not on oxidative capacity, mitochondrial content and capillary density, suggesting that intensity of exercise contributes to the VO_2peak change. Gjellesvik *et al.* [23] and Globas *et al.* [22] executed a long-term follow-up assessment (1-year) about VO_2peak. The value for VO_2peak achieved from training had been maintained. These findings positively confirmed again the feasibility and benefit of activity intervention for the increase in aerobic performance. However, Holleran *et al.* [27] did not find significant change in VO_2peak after high intensity exercise in stroke ($p = 0.48$), similar with Askim *et al.* [28] ($p = 0.19$). This confounding of VO_2peak change may due to the different exercise protocols and interval time across studies. Moreover, the small sample size and patients' condition are important reasons. HIIT might be deemed benefit for the improvement of cardiopulmonary function and reduction of mortality rate in stroke.

Walking performances are important for stroke patients to maintain their own lives and participate in family, social activities, which are usually evaluated using 6-min walk distance (6MWD). The walking economy (Cw) test and 10-meter Walk Test (10MWT) are occasionally adopted in some literatures. Askim *et al.* [28] found significant increase in 6MWD from pretreatment (mean 410.7 m) to post-treatment (mean 461.0 m) ($p = 0.001$). This improvement sustained and attained a significantly change ($p < 0.001$) during 12 weeks follow-up, which was in line with the results from Calmels *et al.* [24], a similar increase in walking performances with the 6MWT (mean increase 15.87%, $p = 0.0002$). The study of Outermans *et al.* [29] recruited 22 patients with subacute stroke, which showed an increment of 54.0 m (SD 65.1) to mean 518.7 m (standard deviation [SD] 165.2) in 6MWT after high intensity interval task-oriented training compared with a smaller increment [(21.4 ± 43.2) m to (422.4 ± 127.9) m] in the low intensity physiotherapy-group. Similarly, the improvement on the 10MWT was reported [(0.3 ± 0.3) m/s to (1.7 ± 0.5) m/sec] compared with a level of post-trial [(1.4 ± 0.4) m/sec] in the low-intensity physiotherapy-group. Notably, HIIT did not significantly improve Berg Balance Scale (BBS) scores (Hedges' $g = 0.07$, 95% *CI*: −0.13 – 0.26, shown in Fig. 3). This null effect aligns with prior findings and underscores the task-specificity of training adaptations. Balance relies heavily on sensorimotor integration, anticipatory postural adjustments, and lower-limb strength—elements not explicitly targeted by aerobic-focused HIIT protocols. Additionally, ceiling effects in high-functioning chronic stroke survivors may mask subtle improvements. Future protocols should integrate dynamic balance challenges (*e.g.*, inclined treadmill walking, obstacle negotiation) to address this gap.

5 Conclusion

HIIT is a safe, high-efficacy intervention for improving aerobic capacity and walking capacity post-stroke. Its benefits are maximized at higher intensities. While balance improvements require complementary training, HIIT should be integrated into stroke rehabilitation guidelines as a cornerstone for enhancing functional independence.

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