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Effectiveness of Treadmill Training Intervention for the Management of Patients With Stroke: A Systematic Review and Meta-Analysis

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ABSTRACT

Background: Treadmill training, including body weight–supported treadmill training (BWSTT), is widely used in stroke rehabilitation. However, its efficacy in improving walking outcomes may vary depending on patients' baseline functional status.

Objective: This study aims to systematically evaluate effectiveness of treadmill training on walking speed and endurance in stroke survivors and to assess influence of baseline dependency and use of BWSTT.

Methods: We performed systematic review and meta-analysis as per PRISMA 2020 guidelines. Comprehensive search was conducted using Scopus, MEDLINE, EMBASE, Chinese Biomedical Literature Database, China National Knowledge Infrastructure, Cochrane Library, Google Scholar and ScienceDirect for studies published from January 1964 to April 2024. Eligible studies were randomized controlled trials assessing treadmill training in stroke patients with outcomes as walking speed and/or endurance. Data extraction and risk of bias assessment were independently performed by two reviewers using Cochrane Risk of Bias-2 tool. Standardized mean differences (SMDs) and 95% confidence intervals (CIs) were calculated using random effects model. Subgroup analyses were conducted based on baseline dependency and BWSTT use.

Results: Fifty-nine studies were included. Meta-analysis demonstrated significant improvements in walking speed (SMD = 0.255; 95%CI: 0.141–0.369) and walking endurance (SMD = 0.277; 95%CI: 0.134–0.421) among stroke survivors receiving treadmill training. Subgroup analysis revealed that independent participants experienced greater benefits in walking speed (SMD = 0.345) and endurance (SMD = 0.374) compared to dependent participants. Studies employing BWSTT reported enhanced outcomes relative to those without BWSTT. Moderate to high heterogeneity was observed, and publication bias was detected.

Conclusion: Treadmill training, particularly when combined with BWSTT, effectively enhances walking speed and endurance in stroke survivors.

1 | Introduction

Stroke represents a significant global health challenge, affecting millions of individuals annually and leading to a wide range of disabilities (Khaku and Tadi 2024). These disabilities can vary widely from mild impairments to severe physical and cognitive dysfunction, depending on the stroke's severity and the brain area affected (Elendu et al. 2023). Despite advances in acute stroke management, the long-term rehabilitation of stroke survivors remains a critical area for healthcare providers

Summary

- What Is Already Known About This Topic?
- Treadmill training, including body weight-supported treadmill training (BWSTT), is a potential rehabilitation intervention for stroke survivors to improve walking speed and endurance.
- Previous studies have shown mixed results regarding the effectiveness of treadmill training compared to other rehabilitation methods.
- Key knowledge gaps include the differential impact of treadmill training based on patients' initial functional status and the specific benefits of incorporating BWSTT.
- What This Paper Adds?
- This meta-analysis demonstrates significant improvements in walking speed (SMD = 0.255) and walking endurance (SMD = 0.277) in stroke survivors following treadmill training.
- Subgroup analyses reveal that independent participants benefit more significantly in both walking speed and endurance compared to dependent participants.
- Studies employing BWSTT show greater improvements in walking outcomes, highlighting the added value of this technique in stroke rehabilitation.
- The Implications of This Paper
- How do these findings influence policy?
- These findings suggest that treadmill training, especially with BWSTT, should be considered for inclusion in standard stroke rehabilitation programs due to its effectiveness in improving mobility.
- How can these findings be used in practice?
- Clinicians can better tailor rehabilitation programs by incorporating treadmill training, particularly for patients who are initially independent, to maximize improvements in walking speed and endurance.
- How do these findings impact research and education?
- Future research should focus on standardizing treadmill training protocols, comparing different types of treadmill interventions and exploring long-term outcomes. Educational programs should emphasize the benefits of treadmill training in stroke rehabilitation.

and researchers, with the primary goal of enhancing functional recovery and improving quality of life (Boehme et al. 2021). Moreover, as walking is pivotal to autonomy and overall well-being, regaining independent ambulation is widely recognized as the primary goal in stroke rehabilitation.

Treadmill training, as a form of physical therapy, has gained prominence in poststroke rehabilitation programs (Damiano and DeJong 2009). This intervention leverages the natural pattern of walking, which is often severely affected following a stroke. The rationale behind treadmill training is based on the concept of neuroplasticity—the brain's ability to reorganize itself by forming new neural connections (Harvey 2009; Xiao et al. 2012). This ability allows for the compensation of damaged areas and the restoration of lost functions to some extent. Additionally, treadmill training is believed to stimulate central pattern generators (CPGs) in the spinal cord—intrinsic neural circuits that generate rhythmic and coordinated movements—thereby supporting the recovery of automatic, independent walking patterns in stroke survivors (Sun et al. 2013).

One of the key advantages of treadmill training includes its ability to provide a controlled environment where the intensity, speed and duration of exercise can be systematically adjusted to meet the specific needs of each patient (McCain et al. 2008). This customization is crucial since stroke survivors often exhibit varied levels of motor function impairments. Moreover, modern treadmills equipped with body weight support systems can further assist those who are initially unable to support their weight or maintain balance, thereby facilitating an earlier start to walking exercises than might otherwise be possible (Yamamoto et al. 2022).

The effectiveness of treadmill training in the rehabilitation of patients with stroke has been supported by various studies highlighting improvements in gait speed, endurance and overall walking ability (Deniz et al. 2011; DePaul et al. 2015; Kelley et al. 2013; Kaźmierczak et al. 2022). These enhancements are critical, as they contribute directly to the independence and quality of life of stroke survivors. However, the degree to which treadmill training is beneficial when compared to other rehabilitation interventions remains a subject of considerable debate within the medical community.

Furthermore, the timing of intervention initiation poststroke is a pivotal factor that potentially influences the outcomes of treadmill training (Deniz et al. 2011; DePaul et al. 2015; Kaźmierczak et al. 2022; Kelley et al. 2013). Early intervention may capitalize on the heightened state of neuroplasticity immediately following a stroke, possibly leading to more significant improvements in motor skills (Laufer et al. 2001; McCain et al. 2008). Conversely, late initiation of treadmill training, while still beneficial, might not offer the same level of impact due to the reduced plasticity of the brain as time progresses (Aguiar et al. 2020; Baek et al. 2021; Brauer et al. 2022; Hornby et al. 2019; Kim and Yim 2017; Nave et al. 2019; Serra et al. 2022; Cakmak et al. 2024).

Adding to the complexity, individual characteristics of patients with stroke—such as severity of stroke, specific brain regions affected and the presence of other comorbid conditions—can significantly modify the effectiveness of any rehabilitation technique, including treadmill training. Therefore, personalized approaches to rehabilitation, which consider these individual differences, are increasingly advocated in clinical settings.

In this context, comprehensive review of available literature on treadmill training for patients with stroke can provide valuable insights. By aggregating and analysing data from multiple studies, this approach offers a robust assessment of the effectiveness of treadmill training interventions, helping to clarify their benefits and limitations. Such an analysis is crucial not only for clinicians seeking to optimize rehabilitation strategies but also for stakeholders involved in health policy and resource allocation

in stroke care. Hence, this review was done to determine the effectiveness of treadmill training intervention for managing patients with stroke.

2 | Materials and Methods

2.1 | Eligibility Criteria

The inclusion criteria are defined as follows:

Study Design: Only individual or cluster randomized controlled trials (RCTs) with a parallel arm or cross-over structure were included.

Publication Criteria: The review has considered only published full-text articles. Case reports, series, conference abstracts and unpublished grey literature will be excluded.

Population: Studies targeting patients diagnosed with stroke (ischaemic or haemorrhagic), without limitations based on age, gender or the presence of comorbidities.

Interventions: Studies that evaluate the effectiveness of treadmill training interventions for stroke rehabilitation. Comparisons may include standard care practices or other rehabilitative interventions.

Outcomes: Studies must report on any of the following outcomes: walking speed and walking endurance.

2.2 | Search Strategy

A comprehensive and meticulous literature search was conducted across multiple databases, including Scopus, MEDLINE, EMBASE, Chinese biomedical literature database, China National Knowledge Infrastructure, Cochrane Library and search engines like Google Scholar and ScienceDirect. We employed both medical subject headings (MeSH) and free-text terms, using Boolean operators to refine the search. The key terms were related to stroke, treadmill training and randomized controlled trials. The search was limited to articles published from January 1964 to April 2024 and was conducted in both English and Chinese languages. Additionally, we examined the references of the retrieved studies to identify any potentially overlooked articles. The search strategy for this review is outlined in the Supporting Information Appendix.

2.3 | Study Screening

During the initial phase of study selection, titles, keywords and abstracts were independently screened by two reviewers. Subsequently, they accessed and assessed the full texts of potentially relevant studies based on the pre-established eligibility criteria. Any discrepancies during the initial screening phase were settled through discussion and consensus between the two reviewers. In the second phase, thorough examination of full texts was performed, finalizing those studies that fulfilled the inclusion criteria.

2.4 | Data Extraction

After identifying the studies suitable for inclusion, the two reviewers engaged in data collection using a specially designed semistructured data extraction form, which was developed during the planning phase of the review. This form facilitated the systematic collection of critical information such as the authors' names, title of the study, publication year, study duration, research design, location and setting of the study, number of participants, tools used for outcome assessment, average age of participants and detailed descriptions of the interventions and control conditions. Data entry was conducted by the first reviewer and subsequently checked for precision by the second reviewer.

2.5 | Risk of Bias Assessment

The primary and secondary researchers undertook the responsibility of evaluating the risk of bias in the studies that were included. They employed the Cochrane Risk of Bias tool for Randomized Controlled Trials (RoB 2) to scrutinize five distinct areas: bias stemming from the randomization process, deviations from the planned intervention, incomplete outcome data, the accuracy of outcome measurement and bias in the reporting of results (Sterne et al. 2019). Following these evaluations, each study was classified as exhibiting low, high or moderate concerns related to bias, which in turn helped to ascertain the quality of the evidence provided.

2.6 | Statistical Analysis

Meta-analysis was performed using STATA software, version 17. Since both the outcomes were continuous, standardized mean difference (SMD) was computed along with 95% confidence intervals (Cis), using means, standard deviations and sample sizes from each group. Random effects model was utilized, applying the inverse variance method for the weighting of studies. Forest plots were created to illustrate both individual study results and combined estimates (Cumpston et al. 2019).

Heterogeneity among the studies was evaluated using chi-square test and I^2 statistics. Subgroup analyses were carried out focusing on variables such as the independence of participants at the time of recruitment and the use of body weight-supported treadmill training (BWSTT) techniques. For the purposes of this review, 'dependent group' is defined as stroke survivors who, at baseline, required physical assistance or relied on assistive devices for ambulation, as determined by standardized functional assessments (e.g., the Functional Ambulation Categories). Importantly, the use of BWSTT is considered an intervention modality and does not, in itself, classify a patient as dependent; rather, dependency is solely based on baseline ambulation ability. Publication bias was examined using Egger's test and visualized through funnel plots. An asymmetrical funnel plot or an Egger's test p-value less than 0.05 was indicative of potential publication bias (Cumpston et al. 2019).

3 | Results

3.1 | PRISMA Flow Diagram

Review process commenced with identification of 3193 records through various databases. After removing 432 duplicates, 2761 records were screened, leading to 238 full-text articles being assessed for eligibility (Figure 1). Ultimately, 59 studies met the inclusion criteria and were incorporated into the review (Ada et al. 2003, 2013; Aguiar et al. 2020; Baek et al. 2021; Bonnyaud et al. 2013a, 2013b; Brauer et al. 2022; Combs-Miller et al. 2014; Da Cunha Filho et al. 2002; Deniz et al. 2011; DePaul et al. 2015; Duncan et al. 2011; Eich et al. 2004; Franceschini et al. 2009; Gama et al. 2017; Globas et al. 2011; Hornby et al. 2008, 2019; Hoyer et al. 2012; Jaffe et al. 2004; Kang et al. 2012; Kaźmierczak et al. 2022; Kelley et al. 2013; Kim et al. 2011, 2016; Kim and Yim 2017; Kosak and Reding 2000; Kuys et al. 2011; Langhammer and Stanghelle 2010; Laufer et al. 2001; Liston et al. 2000; Luft et al. 2008; Mackay-Lyons et al. 2013; Macko et al. 2005; Mao et al. 2015; Middleton et al. 2014; Moore et al. 2010; Nave et al. 2019; Nilsson et al. 2001; Olawale et al. 2009; Park et al. 2013, 2015; Pohl et al. 2002; Ribeiro et al. 2013; Richards et al. 1993, 2004; Serra et al. 2022; Srivastava et al. 2016; Sullivan et al. 2007; Suputtitada et al. 2004; Takami and Wakayama 2010; Cakmak et al. 2024; Toledano-Zarhi et al. 2011; Weng et al. 2004, 2006; Werner et al. 2002; Yen et al. 2008; Zhu et al. 2004).

3.2 | Included Study Characteristics

Characteristics of the included studies are provided in Table 1.

3.3 | Walking Speed

In the meta-analysis, 57 studies involving 2895 participants were included, assessing the effects of treadmill training on walking speed in stroke survivors. The pooled SMD for overall effect was 0.255 (95% CI: 0.141 to 0.369), indicating a significant improvement in walking speed ($z = 4.382$, $p < 0.001$) when compared to control group (Figure 2). Heterogeneity was moderate with an I^2 of 49.3%, suggesting variability in study outcomes that could influence the interpretation of the effects.

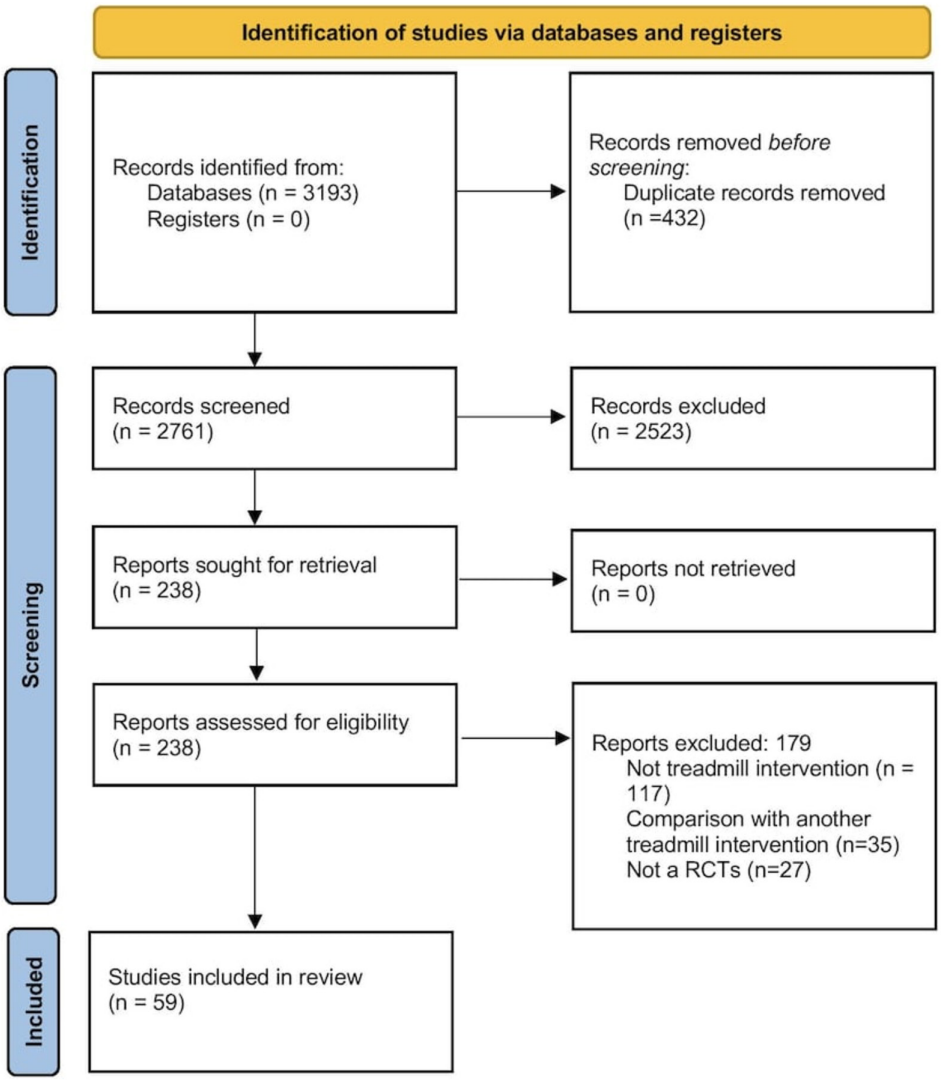

FIGURE 1 | PRISMA flowchart.

TABLE 1 | Characteristics of the included studies ($N = 59$).

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Ada et al. (2003)	Australia	Parallel arm RCT	Patients within 28 days of their first stroke, between 50 and 85 years of age.	Involved walking on a treadmill supported in a harness	Assisted overground walking	6 months	64	62	NR	NR	Low
Ada et al. (2013)	Australia	Three-arm parallel RCT	People with chronic stroke ambulatory at study onset	Group A undertook 30 min of treadmill and overground walking three times per week for 4 months Group B undertook treadmill training for 2 months	No intervention	12 months	34	34	A-63 B-64	70	Low
Aguiar et al. (2020)	NR	Parallel arm RCT	People with chronic stroke	Treadmill Training (40 min, three times/w, 12 weeks Total 1440 min)	Physiotherapy Interventions (40 min, three times/w, 12 w, total 1440 min)	4 months	11	11	52	48	Low
Baek et al. (2021)	South Korea	Single-blind, two-arm parallel RCT	People with chronic stroke	Each intervention comprised allocated treadmill training for 30 min and simple exercise for 30 min in the supine and sitting positions. Simple exercise included only passive stretching in the upper extremity, hip, and knee areas.	Standard care	6 weeks	17	17	56.94	56.13	Low
Bonnyaud et al. (2013a)	France	Four arm Parallel RCT	People with chronic stroke	GO: overground without a mass once for 20 min at comfortable speed GOM: overground with a mass once for 20 min at comfortable speed GT: treadmill without a mass once for 20 min at comfortable speed GTM: treadmill with a mass once for 20 min at comfortable speed	Standard care	20 min	60	NR	50	50	High

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Bonnyaud et al. (2013b)	France	Parallel arm RCT	People with chronic stroke and aged greater than 18 years, hemiparesis caused by a single hemispheric stroke, ability to walk 20 min without a break and without an assistive device	GO: single overground gait-training for 20 min in a corridor at comfortable speed	Gait-training for 20 min at comfortable speed	20 min	26	NR	50	50	High
Brauer et al. (2022)	NR	Parallel arm RCT	People with Subacute stroke	Treadmill Training 9 TT: 30 min, three times/w, 8 weeks Conv GT: 30 min, two times/w, 8 weeks Total 1200 min)	Physiotherapy Interventions (30 min, five times/w, 8 w, total 1200 min)	26 weeks	60	59	62	64	Low
Cakmak et al. (2024)	Turkey	Parallel arm RCT	People with chronic stroke	Treadmill training for 3 consecutive weeks, 5 days a week, for 30 min each day and additional 30 min of BWSTT per session	Control for 3 consecutive weeks, 5 days a week, for 30 min each day	3 weeks	14	16	55	57	High
Combs-Miller et al. (2014)	USA	Parallel arm RCT	Minimum of six months postischaemic or haemorrhagic stroke; age between 21 and 80 years	BWSTT group undertook 30 min of treadmill training with systematically less body weight support (start at 30%), five times per week for 2 weeks	OWT group B undertook overground walking training at fast speed, five times per week for 2 week	2 weeks	10	10	56	66	Low
Da Cunha Filho et al. (2002)	NR	Parallel arm RCT	People with chronic stroke	BWSTT: participants walked on a treadmill with up to 30% of their body weight supported using a harness	Regular gait-training (CTL): strengthening, functional and mobility activities	3 weeks	7	8	NR	NR	Low
DePaul et al. (2015)	Canada	Parallel arm RCT	People with chronic stroke ambulatory at study onset	MLWP group undertook a Motor Learning Walking Program and practiced various overground walking tasks for 40 min, 15 sessions over 5 weeks	BWSTT group undertook a Body weight-supported treadmill Training for 30 min, 15 sessions over 5 weeks	5 weeks	35	35	66	69	Low

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Deniz et al. (2011)	Turkey	Parallel arm RCT	People with chronic stroke ambulatory at study onset	BWSTT, five times per week for 4 weeks (300 min a week)	General physiotherapy, five times per week for 4 weeks (300 min a week)	1 month	10	10	62	62	Low
Duncan et al. (2011)	USA	Parallel arm RCT	People age of 18 years or older, a stroke within 45 days before study entry	Group 1 received training on a treadmill with the use of BWS 2 months after the stroke had occurred (early locomotor training) Group 2 received this training 6 months after the stroke had occurred (late locomotor training)	Controls participated in an exercise program at home managed by a physical therapist 2 months after the stroke (home exercise program)	12 months	408	NR	NR	NR	Low
Eich et al. (2004)	NR	Parallel arm RCT	Patients first time supratentorial stroke; less than 6 weeks post-stroke; aged 50–75 years	Participants walked on a treadmill with up to 15% of their body weight supported using a harness; the slope and speed of the treadmill were adjusted to achieve a training heart rate	Regular gait-training: tone-inhibiting and gait preparatory manoeuvres and walking practice on floor and stairs based on Bobath	3 months	25	25	NR	NR	Low
Franceschini et al. (2009)	Italy	Parallel arm RCT	People with chronic stroke not ambulatory at study onset	Conventional rehabilitative treatment plus gait-training with BWSTT	Conventional treatment with overground gait-training only	1 month	52	50	66	71	Low
Gama et al. (2017)	Brazil	Parallel arm RCT	Chronic hemiparetic gait after an ischaemic or hemorrhagic stroke, > 6 months from the stroke event	Walking on a treadmill supported in a harness with BWSTT	Assisted overground walking with BWS	1 and half months	16	16	NR	NR	Some concerns

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Globas et al. (2011)	Switzerland and Germany	Parallel arm RCT	Hemiparetic gait as evaluated by a neurologist with at least 1 clinical sign for paresis, spasticity or circumduction of the affected leg while walking and ambulatory at study onset	3 months (three times per week) progressive graded, high-intensity aerobic treadmill exercise	Conventional care physiotherapy	3 months	20	18	69	69	Some concerns
Hornby et al. (2008)	USA	Parallel arm RCT	People with chronic stroke	Locomotor training (LT) using a treadmill	Conventional rehabilitation	6 months	24	24	57	57	Low
Hornby et al. (2019)	NR	Parallel arm RCT	People with chronic stroke, able to walk ind ± aids at comf gait speed < 1.0 m/s over 10 m	First group: 33 min, mean 3.375 times/w, 8 weeks Total 891 min Second group: 34 min, mean 3.375 times/w, 8 weeks Total 918 min	Stepping activities in variable contexts (37 min per session, three to five times/w, for 8 weeks Total 999 min)	3 months	30	32	60	56	Some concerns
Hoyer et al. (2012)	Norway	Parallel arm RCT	People with chronic stroke	Treadmill therapy	Traditional gait-training	3 months	30	30	52	52	Low
Jaffe et al. (2004)	NR	Parallel arm RCT	Post-stroke patients. Hemiplegia secondary to documented lesion; able to walk independently or with stand-by supervision	Treated as outpatients for 6 x 1-h sessions per week for 2 weeks	Stepping over real objects while walking overground	2 weeks	11	12	NR	NR	Some concerns
Kang et al. (2012)	South Korea	Parallel arm RCT	People with chronic stroke	3 arms: 1. Wore a head-mounted display to receive speed modulated optic flow during treadmill training for 30 min 2. Treadmill training	3. Regular therapy for the same time, three times per week for 4 weeks	1 month	11 111	10	56	56	Low

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Kaźmierczak et al. (2022)	Poland	Parallel arm RCT	People with chronic stroke aged 63 ± 12 years, with post-ischemic subacute (within six months onset) stroke hemiparesis	Specific rehabilitation program plus additional treadmill training	Specific rehabilitation program	1 month	62	30	63	63	Low
Kelley et al. (2013)	USA	Parallel arm RCT	People with chronic stroke	Robotic-assisted body weight supported treadmill training using the Lokomat®	Ground gait training	2 months	11	9	67	64	High
Kim et al. (2011)	South Korea	Parallel arm RCT	Stroke, able to maintain standing independently for 30 s and to walk independently more than 30 m and able to understand and follow instructions	Treadmill training	Lower extremity muscle strength training	1 and half month	20	24	NR	NR	Some concerns
Kim et al. (2016)	South Korea	Parallel arm RCT	Hemiplegia participants over six months after stroke, gait speed of less than 0.8 m/s,	VRCA group undertook a virtual reality treadmill training-based community ambulation for 30 min, 12 sessions, 3 sessions per week CA group undertook a community ambulation training, 30 min per session, three times per week for 4 weeks	General exercise program, 10 x 30-min sessions per week for 4 weeks	1 month	10 in VRCA, 10 in CA group	10	VRCA-63 CA-64	70	Low
Kim and Yim 2017	South Korea	Parallel arm RCT	People with chronic stroke, able to independently walk	Treadmill training + handgrip strengthening + conventional rehabilitation	Conventional rehabilitation	8 months	14	15	51	52	Low

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Kosak and Reding 2000	NR	Parallel arm RCT	People with chronic stroke	Participants walked on a treadmill and were provided with manual guidance for weight shifting, leg advancement, and foot placement	Participants walked with the assistance of knee–ankle combination bracing and a hemibar (nontask-oriented - 'orthopaedic')	3 months	22	34	NR	NR	Low
Kuys et al. (2011)	Australia	Parallel arm RCT	Diagnosis of first stroke confirmed by CT scan and scored 2 or more on the walking item of Motor Assessment Scale	Walked on the treadmill for 30 min (excluding rests), three times a week for 6 weeks, at an intensity of 40% to 60% heart rate reserve or a Borg Rating of Perceived Exertion of 11 to 14	Usual physiotherapy intervention only	4 and half months	15	15	72	63	Low
Langhammer and Stanghelle 2010	Norway	Parallel arm RCT	People with chronic stroke	Treadmill training (with handrails to hold on but no body weight or other safety support)	Walking outdoors	17 days	21	18	75	74	Low
Laufer et al. (2001)	NR	Parallel arm RCT	Participants with onset of stroke no more than 90 days prior to recruitment and ability to walk on treadmill.	Participants walked on a treadmill at a comfortable speed with a therapist assisting leg movements and were permitted to use a handrail for external support if required;	Participants walked on a floor surface using gait aids, assistance, and rest periods as needed	3 weeks	15	14	NR	NR	High
Liston et al. (2000)	NR	Cross-over RCT	People with higher level gait disorder and discharged from all rehabilitation services.	Participants walked on a treadmill for as long as they felt comfortable, rest breaks were allowed and no body weight support was provided using a harness	Schedule of 31 interventions in 3 treatment modules: gait ignition or failure, postural alignment and other	1 and half months	10	8	NR	NR	Low

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Luft et al. (2008)	USA	Parallel arm RCT	People older than 45 years of age with first clinical ischaemic stroke and chronic hemiparetic gait 6 or more months after completion of conventional subacute rehabilitation	Treadmill training sessions. Duration and intensity started low and increased approximately by 5 min and 5% heart rate reserve every 2 weeks	Standard Care	6 months	57	56	64	63	Low
Mackay-Lyons et al. (2013)	Canada	Parallel arm RCT	People older than 18 years, within 1 month of a first ischaemic stroke able to walk 5 m with or without assistance	All individuals participated in 60-min physiotherapy sessions five times weekly as inpatients for 6 weeks and three times weekly as outpatients for another 6 weeks for a total of 48 sessions.	Standard Care	6 and 12 months	24	26	62	59	Low
Macko et al. (2005)	NR	Parallel arm RCT	People with Chronic ischaemic stroke (less than 6 months)	Participants walked on a treadmill to achieve a target aerobic intensity of 60% to 70% heart rate reserve (progressive aerobic training); no body weight support was provided using a harness	Participants completed a supervised stretching and low-intensity walking program	6 months	32	29	NR	NR	Low
Mao et al. (2015)	China	Parallel arm RCT	People with first stroke, unilateral hemiparesis for no more than 3 months resulting and abnormal 10 m walk time	Received body weight-supported treadmill training 20 to 40 min five times per week for 3 weeks	Underwent conventional overground walking for same amount of time	NR	15	14	60	NR	Some concerns

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Middleton et al. (2014)	USA	Parallel arm RCT	People with age ≥ 18 years and presence of unilateral hemiplegia	Undertook gait-training on a treadmill with comfortable speed for 60 min and 120 min training for balance, strength, coordination and range of motion for 10 consecutive weekdays	Received an overground gait-training including training for balance, strength, coordination and range of motion, 3 h for 10 consecutive weekdays (total of 30 h)	3 and half months	27	23	61	61	High
Moore et al. (2010)	USA	Cross-over RCT	People who are ≤ 3 months after stroke, ability to stand or walk 5 m	20/30 participants with chronic stroke completed a repeated baseline measure with clinical physiotherapy; afterwards participants were randomized in a cross-over trial and received 4 weeks of intensive locomotor training (A) or 4 weeks of no intervention (B) before cross over	Standard Care	NR	15	15	67	57	Some concerns
Nave et al. (2019)	Germany	Parallel arm RCT	People who are aged more than 18 years, were in the subacute phase of ischaemic or haemorrhagic stroke	Participants received either aerobic, bodyweight supported, treadmill based physical fitness training or relaxation sessions, each for 25 min, five times weekly for 4 weeks	Relaxation sessions, that is, participants were instructed to contract the muscles for five to 10 s	6 months	105	95	69	70	Some concerns
Nilsson et al. (2001) (a)	NR	Parallel arm RCT	First stroke with residual hemiparesis and aged less than 70 years	Participants walked on a treadmill with up to two therapists assisting leg movements, they were permitted to use a handrail for external support, if required	Participants practiced walking on a floor surface based on Motor Relearning Program guidelines	10 months	26	28	NR	NR	Low

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Nilsson et al. (2001) (b)	NR	Parallel arm RCT	First stroke with residual hemiparesis and aged less than 70 years	Participants walked on a treadmill with up to 2 therapists assisting leg movements, they were permitted to use a handrail for external support, if required	Participants practiced walking on a floor surface based on Motor Relearning Program guidelines	10 months	10	9	NR	NR	Low
Olawale et al. (2009)	Nigeria	Three-arm parallel RCT	People who had stroke > 3 months but < 24 months and can walk independently	Treadmill training for, three times a week for 12 weeks (3 h a week)	Control group 1 used standard physiotherapy, three times a week for 12 weeks (3 h a week) 2. CTL Control group 2 used standard physiotherapy including overground walking exercises for the same time and frequency	3 months	20	40	57	57	Some concerns
Park et al. (2013)	South Korea	Two arm parallel RCT	Participants with onset of stroke 6 months or more prior to the study and can walk for 10 m or more without any aid	1. OGT group undertook overground gait-training for 30 mins twice a day for 5 days 2. TGT group received treadmill gait-training with increased speed for same amount of time	Not reported	NR	20	20	53	53	Some Concerns
Park et al. (2015)	South Korea	RCT	People > 6 months and < 2 years after the onset of stroke can walk for 10 min or longer on a treadmill and also absence of neurotic diseases.	Group undertook treadmill walking training with rhythmic auditory stimulation 30 min, five times per week for 3 weeks	Group received overground walking training with rhythmic auditory stimulation for the same amount of time	NR	9	10	53	53	High

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Pohl et al. (2002)	NR	Parallel arm RCT	People with hemiparesis are caused by ischaemic stroke and are able to walk without assistance.	Participants walked on a treadmill without therapist assistance, speed was progressed using an aggressive protocol Limited progressive treadmill training with body weight support.	Conventional gait therapy	NR	44	25	NR	NR	Some concerns
Ribeiro et al. (2013)	Brazil	Parallel arm RCT	People of age 40 to 70 years with chronic stroke	Group underwent treadmill gait-training base—30 min three times per week for 4 weeks	Training with comfortable speed for same amount of time	NR	12	13	57	57	High
Richards et al. (1993)	NR	Parallel arm RCT	People aged 40 to 80 years and less than 7 days after onset of first stroke.	Treatment started as early as possible after the stroke and included treadmill training, tilt table exercises and resisted exercises using isokinetic equipment.	Control group 1: Traditional physiotherapy based on neurophysiological techniques. Control group 2: Less intense traditional physiotherapy based on neurophysiological techniques	3 to 6 months	10	17	NR	NR	Some concerns
Richards et al. (2004)	Canada	RCT	People aged between 30 and 89 years, with the first or second episode of ischaemic stroke with residual deficit.	Received treadmill training without body weight support, reciprocal stepping and limb loading for the same time and frequency	Received physiotherapy in an eclectic approach, five times per week for 8 weeks (5 h per week)	3 months	32	31	63 Years	61 Years	Low
Serra et al. (2022)	USA	Parallel arm RCT	People with > 50 years chronic (> 6 months) stroke survivors with hemiparetic gait Were recruited	Participants completed three times /week aerobic treadmill rehabilitation	Six months of two times/week stretching/balance	6 months	19	20	68	63	Some concerns

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Srivastava et al. (2016)	India	Three-arm parallel RCT	People aged 16 to 65 years with duration of hemiparesis > 3 months and impaired ability to walk independently or with support	One group received gait-training on a treadmill without bodyweight support. Another group received gait-training on a treadmill with partial body weight support (40% unweighting of body weight) all groups trained 30 mins per day, 5 day per week for 4 weeks	Overground task-oriented gait-training.	3 months	45	15	46	46	Low
Sullivan 2007	USA	Four arm parallel RCT	People aged 18 and above, ischaemic or haemorrhagic stroke	Group 1 received combined body weight-supported treadmill training and upper extremity ergometry for the same time and frequency. Group 2 received combined body weight-supported treadmill training and resistive leg cycling for the same time and frequency. Group 3 received combined body weight-supported treadmill training and lower extremity progressive-resistive exercise for the same time and frequency	Combined resistive leg cycling and upper-extremity ergometry, four times per week for 6 weeks (4 h per week)	6 months	60	20	60	63	Low
Suputtitada et al. (2004)	Thailand	Parallel arm RCT	People who have stroke > 6 months prior to enrolment, are able to sit independently.	BWSTT for seven times per week for 4 weeks (2.9 h per week)	Overground walking, seven times per week for 4 weeks (2.9 h per week)	NR	24	24	61	65	Some concerns

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Takami and Wakayama 2010	Japan	Three-arm parallel RCT	People who receive physical therapy, being able to walk 10 m unassisted	Group 1 received a control treatment six times a week for 3 weeks (3 h total) and also had treadmill training six times a week for 3 weeks (1 h total) Group 2 received control intervention six times per week for 3 weeks (3 h per week) and additional body weight-supported treadmill training in backward direction six times per week for 3 weeks (1 h per week)	CTL group received conventional physiotherapy including overground walking, six times per week for 3 weeks (4 h per week) plus ADL training five times per week for 3 weeks (3.3 h)	3 weeks	24	12	71	67	Some concerns
Toledano-Zarhi et al. (2011)	Israel	Parallel arm RCT	People with ischaemic stroke within 1 to 3 weeks before the trial	Supervised exercise program including treadmill training twice per week for 6 weeks (180 min per week exercise training, including 70 to 110 min per week treadmill training) additionally to the control intervention	Home exercise booklet with included instructions for flexibility and muscle strength exercises	NR	14	14	65	65	Some concerns
Weng et al. (2004)	China	Parallel arm RCT	Comply with the Fourth National Stroke diagnostic criteria and able to walk more than 10 m	Received five daily sessions of 20 min of body weight-supported treadmill training for 4 weeks	Received five daily sessions of 20 min conventional training for 4 weeks	4 weeks	25	25	55	55	High
Weng et al. (2006)	China	Parallel arm RCT	Comply with the Fourth National Stroke diagnostic criteria and able to walk more than 10 m	Received five daily sessions of 30 min conventional training and 30 min of additional backward walking with body weight support on a treadmill for 3 weeks	Received five daily sessions of 60 min conventional training for 3 week	3 weeks	13	13	51	50	Low

(Continues)

TABLE 1 | (Continued)

Author and year of publication	Study country	Study design	Participant details	Intervention details	Control details	Duration of follow-up	Sample size (*I*)	Sample size (*C*)	Mean age (in years) (*I*)	Mean age (in years) (*C*)	Risk of bias
Werner et al. (2002)	Not mentioned	Cross-over RCT	People whose age less than 75 years with first stroke and able to stand for at least 10 s	Participants walked on a treadmill with partial body weight support provided by a harness	Participants walked on a Gait Trainer with partial body weight support provided by a harness	6 weeks	15	15	NR	NR	Low
Yen et al. (2008)	Taiwan	Parallel arm RCT	Participants with unilateral stroke with unilateral hemiparesis, ≥ 6 months poststroke	Group additionally to the control intervention, received 12 additional sessions of BWSTT, three times per week for 4 weeks (90 min per week)	Group used general physiotherapy, two to five times per week for 4 weeks (100 to 250 min per week)	4 weeks	7	7	57	56	Low
Zhu et al. (2004)	China	Parallel arm RCT	People aged 30 to 80 years with ischaemic or haemorrhagic stroke are not able to walk.	Participants walked on the Pneu-weight system 5 sessions per week for 4 weeks (duration of sessions not stated), therapy (duration, body weight support) was tailored to the participants individual capabilities	Conventional functional gait-training 5 sessions per week for 4 weeks (duration of sessions not stated)	4 weeks	10	10	57	58	Some Concerns

Abbreviations: BWSTT, body weight-supported treadmill training; C, control; I, intervention; m, metres; NR, not reported; RCT, randomized controlled trial; USA, United States of America.

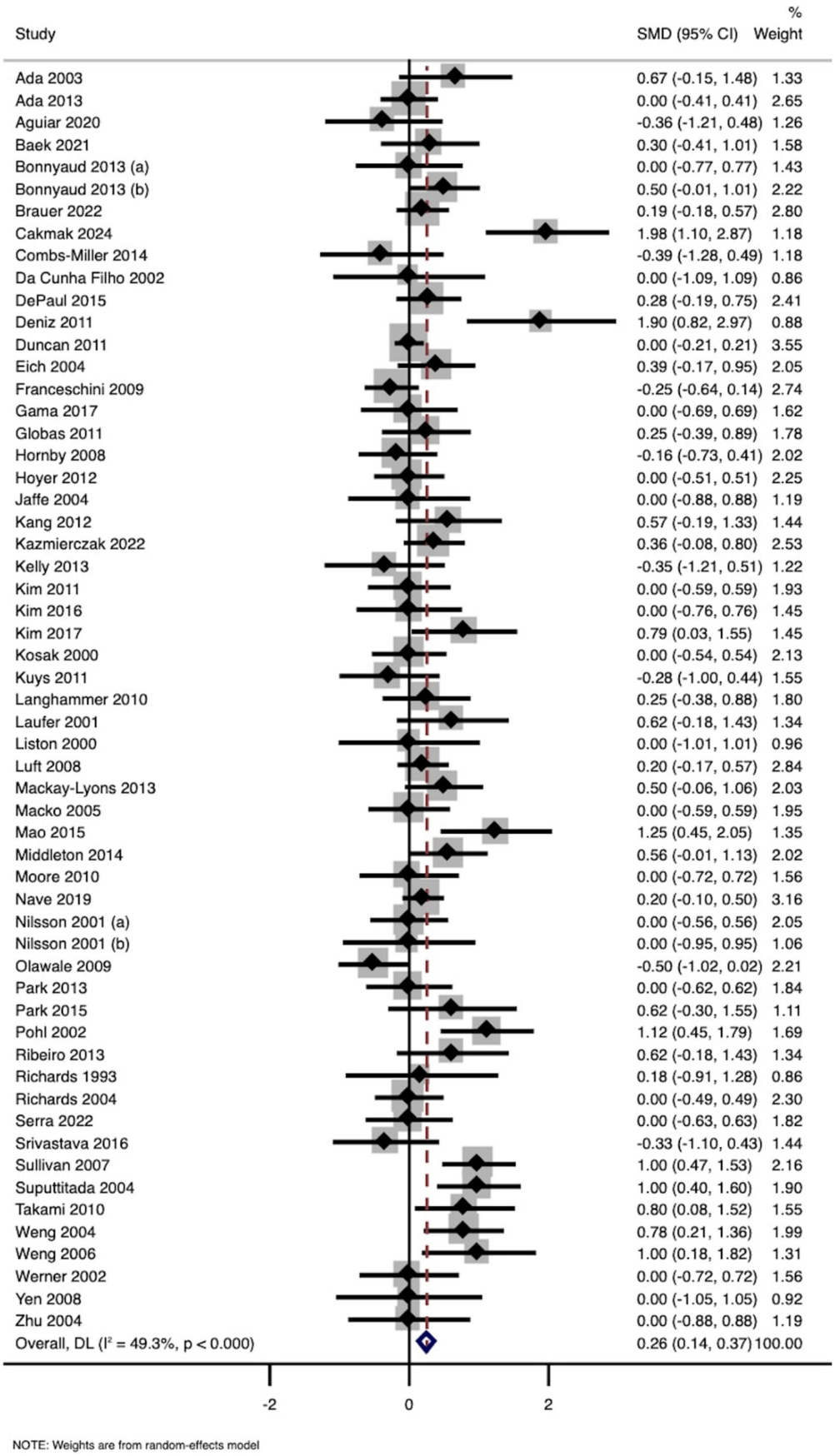

FIGURE 2 | Forest plot showing the effectiveness of treadmill training in improving walking speed among patients with stroke.

Subgroup analysis based on the dependence of the participants at the time of recruitment revealed no significant effect in the dependent group (SMD = −0.004, 95% CI: −0.132 to 0.125), while significant improvement was noted in the independent group (SMD = 0.345, 95% CI: 0.207 to 0.484) (Figure 3). There was moderate heterogeneity in the independent group ($I^2 = 51.3\%$) and minimal heterogeneity in the dependent group ($I^2 = 0.0\%$). Subgroup analysis based on BWSTT combination revealed that the BWSTT subgroup (SMD = 0.316, 95% CI: 0.141 to 0.491) showed significant improvements in walking speed, contrasting the non-BWSTT subgroup which exhibited minimal effect (SMD = 0.184, 95% CI: 0.051 to 0.318) (Figure 4). Publication bias assessment revealed asymmetrical funnel plot with significant Egger's test ($p = 0.040$) (Figure S1).

3.4 | Walking Endurance

The meta-analysis evaluated 38 studies with 2291 participants to assess the impact of treadmill training on walking endurance in stroke survivors. Pooled SMD was 0.277 (95% CI: 0.134 to 0.421), indicating a significant improvement in walking endurance ($z = 3.780$, $p < 0.001$) (Figure 5). However, there was moderate to high heterogeneity among the studies ($I^2 = 58.9\%$), suggesting variation in the effects across different settings and populations.

Subgroup analysis based on the dependence of the participants at the time of recruitment revealed that the independent subgroup (SMD = 0.374, 95% CI: 0.199 to 0.549) had significant improvements in walking endurance, contrasting with the dependent subgroup which demonstrated no significant effect ($n = 38$, SMD = −0.027, 95% CI: −0.166 to 0.111). High heterogeneity was observed in the independent group ($I^2 = 58.4\%$) and minimal heterogeneity in the dependent group ($I^2 = 0.0\%$). (Figure 6). Subgroup analysis based on BWSTT combination revealed that studies without BWSTT (SMD = 0.301, 95% CI: 0.086 to 0.516) and those with BWSTT (SMD = 0.259, 95% CI: 0.063 to 0.455) both demonstrated significant improvements in walking endurance, though the effect sizes were moderate. Moderate heterogeneity was observed within both subgroups (no BWSTT $I^2 = 56.2\%$, yes BWSTT $I^2 = 61.0\%$). (Figure 7). Publication bias assessment revealed asymmetrical funnel plot with significant Egger's test ($p = 0.006$) (Figure S2).

4 | Discussion

This comprehensive meta-analysis encompassing 59 studies focused on the impact of treadmill training on walking speed and walking endurance among stroke survivors, yielding several significant insights. The overall pooled SMD for walking speed was 0.255 (95% CI: 0.141 to 0.369), indicating a substantial improvement. Similarly, for walking endurance, the pooled SMD was 0.277 (95% CI: 0.134 to 0.421), demonstrating notable gains. These findings affirm the efficacy of treadmill training in enhancing functional mobility poststroke.

Subgroup analyses added depth to these findings. For walking speed, participants who were independent at the start of treatment showed a significant improvement (SMD = 0.345, 95% CI: 0.207 to 0.484), while those who were dependent did not exhibit significant changes. This pattern was echoed in the walking endurance outcomes, where the independent subgroup showed substantial improvements (SMD = 0.374, 95% CI: 0.199 to 0.549) but the dependent group did not.

The analysis also highlighted the role of BWSTT, where both walking speed and endurance in groups that utilized BWSTT showed significant improvements compared to those that did not use this method. This suggests that BWSTT could be particularly beneficial in rehabilitation settings.

Publication bias was noted with significant Egger's test results ($p = 0.040$ for walking speed and $p = 0.006$ for walking endurance), indicating potential asymmetry in study reporting, which might influence the perceived effectiveness of treadmill training interventions.

The findings of this meta-analysis are largely consistent with prior research, which has also identified treadmill training as a beneficial intervention for improving gait and endurance in stroke survivors. Studies such as those by Gelaw et al. 2019 and Bishnoi et al. 2022 have similarly reported improvements in walking speed and endurance following structured treadmill programs. However, the distinction between dependent and independent participants in relation to their response to the intervention provides new insights, suggesting that initial functional status is an important determinant of outcome success.

Previous literature has shown mixed results on the efficacy of BWSTT (Mehrholz et al. 2014; Mehrholz et al. 2017). While some studies report significant benefits, others find minimal differences when compared to conventional therapy (Bishnoi et al. 2022; Gelaw et al. 2019; Mehrholz et al. 2014; Mehrholz et al. 2017). Our findings support the notion that BWSTT adds value to the rehabilitation process, likely due to the enhanced safety and ability to initiate training earlier, which is crucial for capitalizing on the window of neuroplasticity soon after the stroke (Mehrholz et al. 2014; Mehrholz et al. 2017).

The significant improvements noted in independent participants align with the principle of "use it or lose it," which is well-documented in neurorehabilitation literature (Fasoli and Adans-Dester 2019). Patients who are more active and retain some degree of functional independence prior to intervention typically experience greater gains due to their ability to engage more fully in therapeutic activities.

The mechanisms underlying the observed benefits of treadmill training in stroke rehabilitation can be attributed to several neurophysiological factors. Treadmill training promotes repetitive, rhythmic limb movements, which are thought to facilitate motor learning and neuroplasticity through the activation of CPGs in the spinal cord. This enhances the efficiency of neural pathways involved in walking, which is crucial for the recovery of functional mobility (Sun et al. 2013).

For BWSTT, the additional support allows patients, even those with severe impairments, to begin walking exercises sooner than they might otherwise. This early mobilization is critical

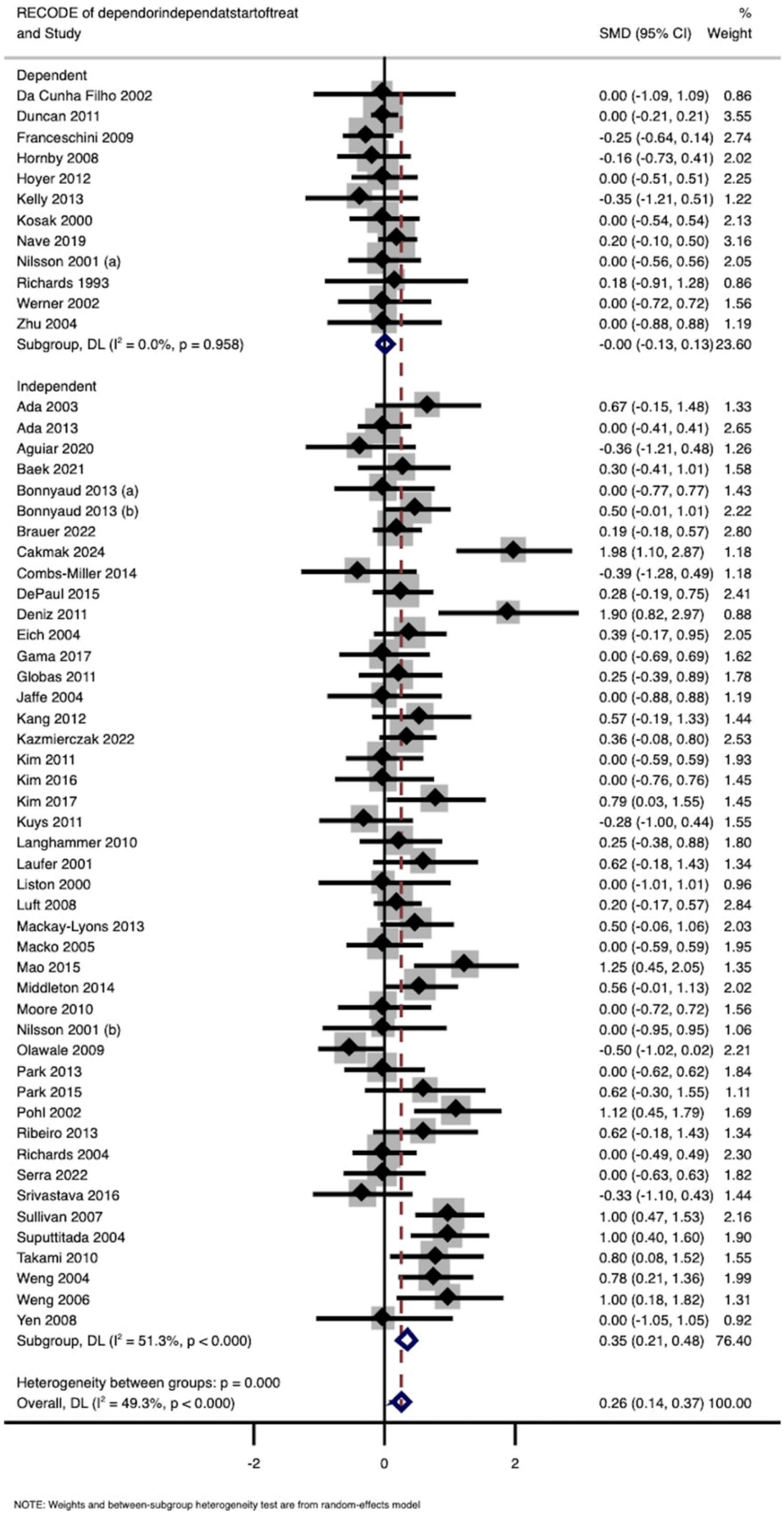

FIGURE 3 | Subgroup analysis based on dependency of the patients at the time of recruitment showing the effectiveness of treadmill training in improving walking speed among patients with stroke.

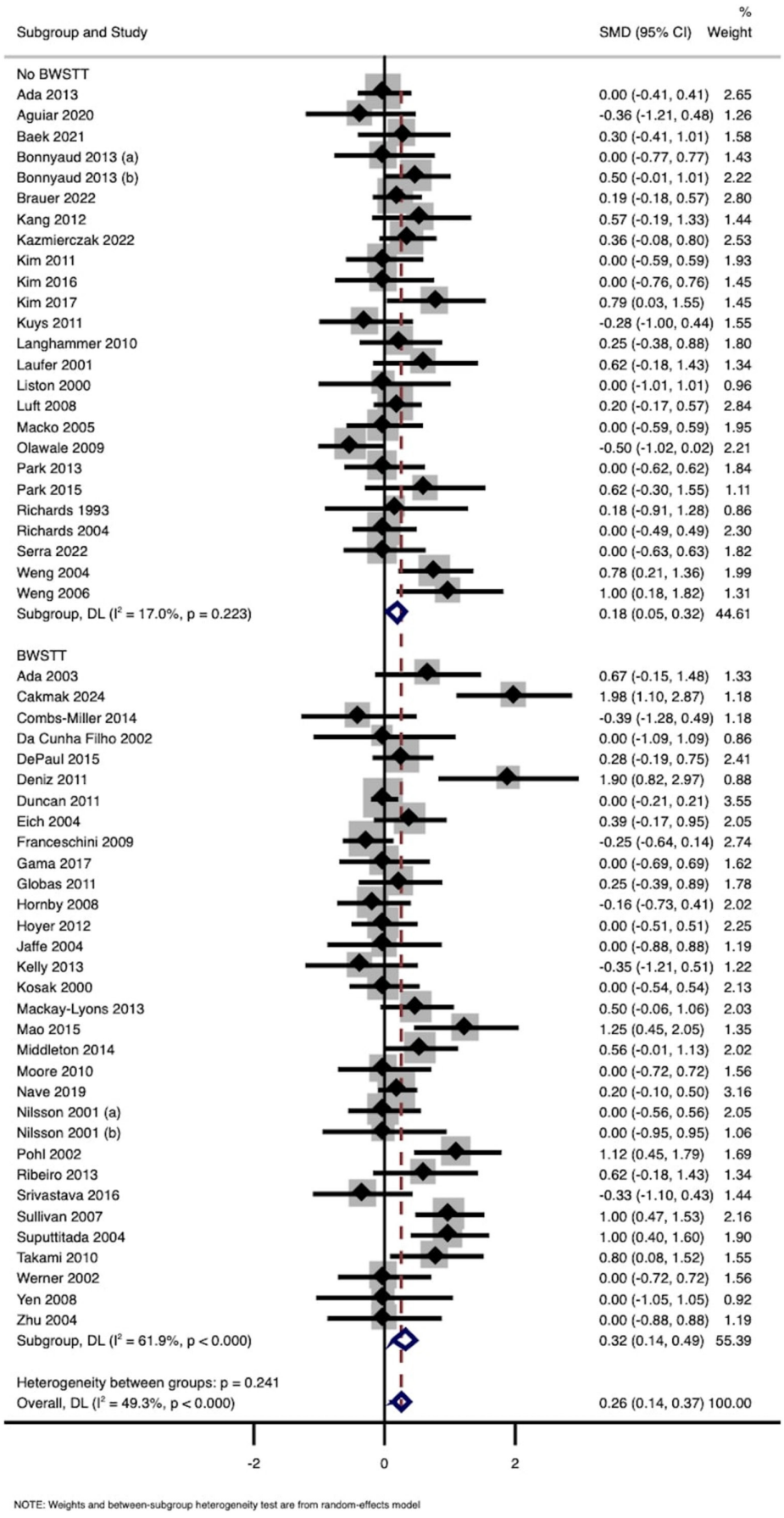

FIGURE 4 | Subgroup analysis based on body weight supported treadmill training showing the effectiveness of treadmill training in improving walking speed among patients withs stroke.

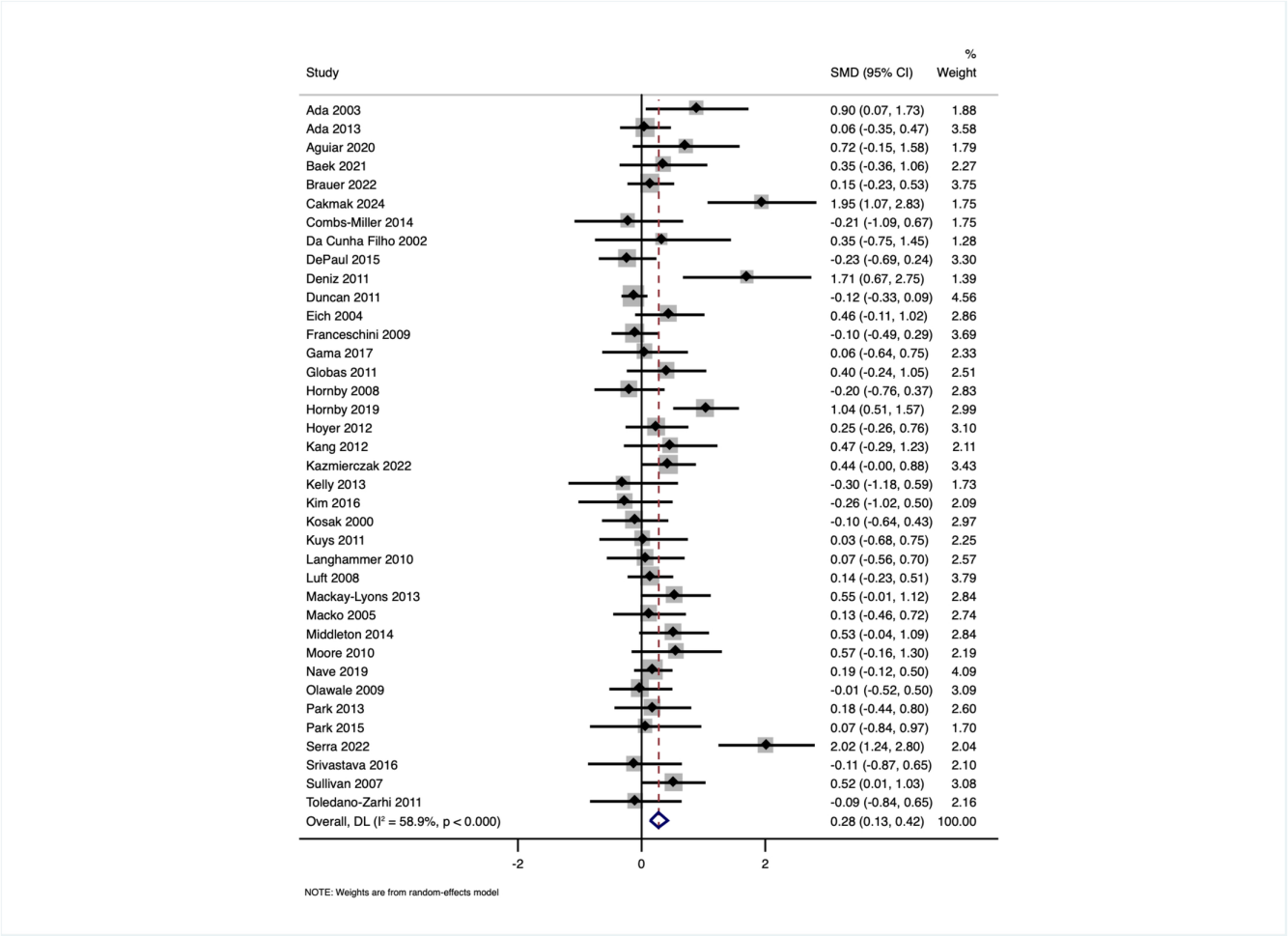

FIGURE 5 | Forest plot showing the effectiveness of treadmill training in improving walking endurance among patients with stroke.

as it helps to mitigate the effects of immobility and capitalizes on the early poststroke period when neuroplasticity is at its peak (Mehrholz et al. 2014; Mehrholz et al. 2017). In addition to facilitating earlier initiation of gait training and reducing fall risk, BWSTT provides a controlled environment that allows for prolonged, repetitive practice of proper gait cycles, which may enhance neuromuscular coordination and motor learning—factors that can directly contribute to improvements in gait speed and endurance (Mehrholz et al. 2014; Mehrholz et al. 2017). Furthermore, beyond the safety benefits, BWSTT enables precise adjustments of training parameters such as treadmill speed, duration and the level of body weight support, allowing therapists to tailor interventions that reinforce efficient gait patterns. This task-specific, repetitive training environment is posited to promote both faster and more enduring improvements in walking performance, as supported by recent evidence (Mehrholz et al. 2014; Mehrholz et al. 2017). For patients with relatively preserved ambulatory function, treadmill training without BWSTT offers a beneficial challenge that promotes greater neuromuscular engagement and strength development, while BWSTT is primarily designed for those with severe impairments who require additional support for safe gait initiation.

The differential outcomes observed between dependent and independent groups may be explained by the varying degrees of motor and neural integrity within these populations. Independent individuals likely retain greater neural reserves and motor capabilities, enabling them to benefit more from the physical and neuroplastic challenges presented by treadmill training. Conversely, individuals who are more dependent may require more tailored interventions that address the specific deficits hindering their mobility (Zeller et al. 2024).

The strengths of this review lie in its comprehensive scope, including a large number of studies and participants, which provides a robust dataset for evaluating the effectiveness of treadmill training. The use of subgroup analyses to explore how different characteristics like initial dependency status and the use of BWSTT influence outcomes adds depth to the findings, offering practical insights for clinical practice.

However, the review is not without limitations. The significant heterogeneity observed across studies suggests variability in study design, participant characteristics, intervention protocols and outcome measures, which could affect the generalizability of the findings. The presence of publication bias also indicates that the results might be skewed towards studies showing positive outcomes, potentially overstating the effectiveness of treadmill training.

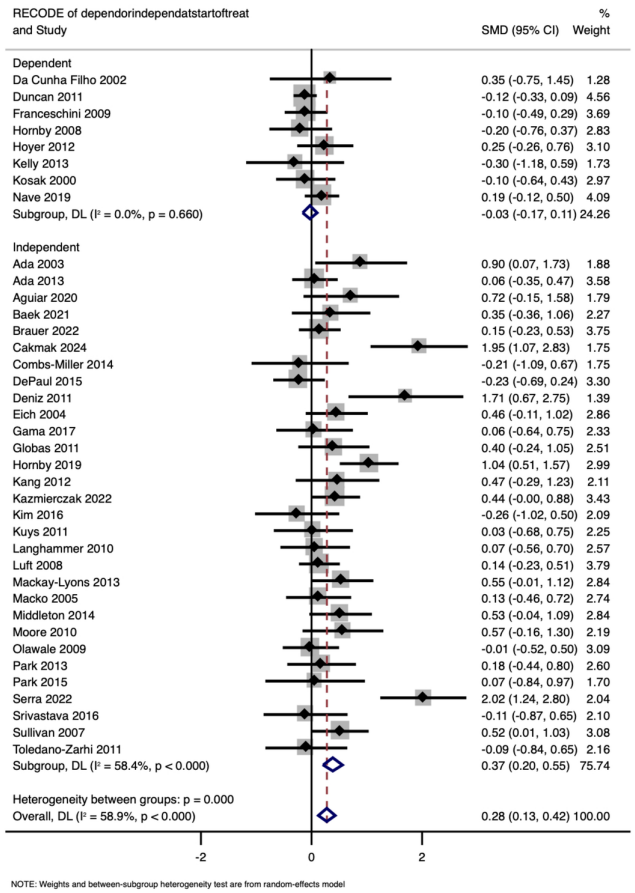

FIGURE 6 | Subgroup analysis based on dependency of the patients at the time of recruitment showing the effectiveness of treadmill training in improving walking endurance among patients with stroke.

The evidence supports the incorporation of treadmill training, particularly BWSTT, into stroke rehabilitation programs, especially for patients who are not severely disabled. Rehabilitation professionals should consider the initial functional status of stroke survivors when designing and implementing treadmill training programs to maximize recovery outcomes. The findings also underscore the importance of early intervention to exploit the window of heightened neuroplasticity poststroke.

Further analysis of our results suggests that the differential outcomes observed between independent and dependent patients may reflect underlying variations in neuromuscular capacity and the ability to engage in repetitive gait training. Independent stroke survivors, who generally have higher residual motor function at baseline, appear better positioned to benefit from the repetitive, rhythmic nature of treadmill training. This may lead to enhanced motor learning and neuroplastic adaptations, thereby facilitating more substantial improvements in walking speed and endurance.

The use of BWSTT further accentuates these effects by enabling safe early mobilization, particularly in patients who may be at risk of falls. BWSTT appears to provide the necessary support that allows patients, especially those with moderate impairments, to practice gait training more intensively and with reduced fear of injury. However, our findings indicate that while BWSTT can enhance walking outcomes, its benefits are more pronounced in individuals with some baseline degree of independence. In contrast, patients classified as dependent—those requiring significant physical assistance or reliance on assistive devices—showed minimal improvement. This suggests that for these patients, additional or alternative rehabilitation strategies (e.g., robotics, targeted strength and balance interventions) may be required to address more severe deficits.

Inference from these observations underscores the importance of tailoring treadmill training interventions based on baseline functional status. Clinicians should consider incorporating BWSTT to maximize early functional gains in patients who are moderately impaired while exploring complementary approaches for those with greater dependency. Future research should aim to refine standardized protocols that adapt treadmill training modalities according to patient-specific needs, ultimately optimizing the potential for functional recovery poststroke.

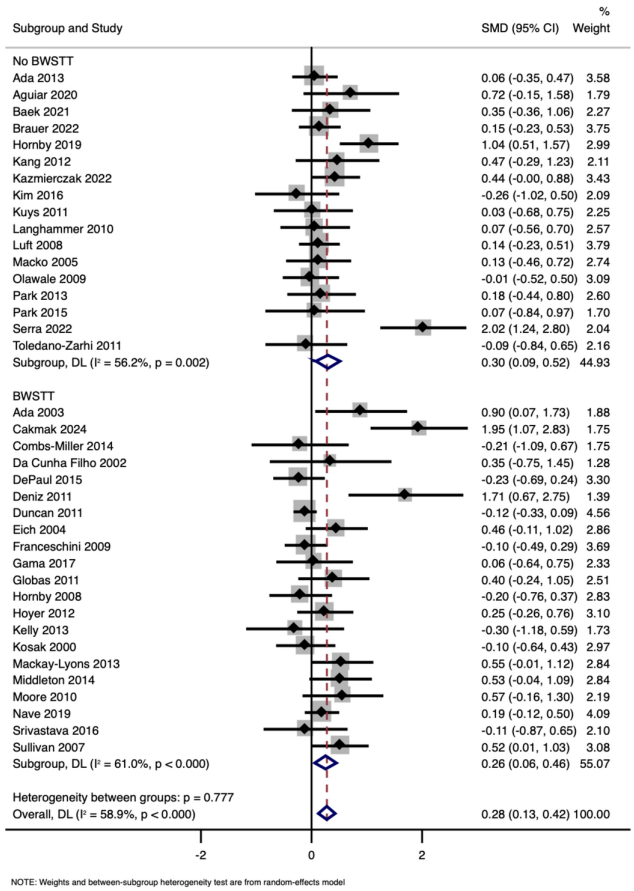

FIGURE 7 | Subgroup analysis based on body weight supported treadmill training showing the effectiveness of treadmill training in improving walking endurance among patients with stroke.

5 | Conclusion

This meta-analysis underscores the efficacy of treadmill training in improving walking speed and endurance among stroke survivors, with notable benefits particularly for those who are independent during study recruitment. The incorporation of BWSTT appears to enhance these benefits, making it a valuable component of comprehensive stroke rehabilitation programs. Despite the challenges posed by heterogeneity and publication bias, the evidence strongly supports the role of treadmill training in enhancing poststroke recovery, meriting its inclusion in clinical practice and further exploration in research.

Author Contributions

All the authors were involved in conception and design of the study, screening, data collection and analysis, writing the first draft, critical appraisal of the article and approval of the final version of the manuscript.

Acknowledgements

The authors have nothing to report.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

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