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REVIEW

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Comparative efficacy of robotic exoskeleton and conventional gait training in patients with spinal cord injury: a meta-analysis of randomized controlled trials

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Abstract

Objective The purpose of this meta-analysis was to investigate the effects of Robotic exoskeleton gait training (REGT) on lower limb mobility, walking balance, functional scores and respiratory function in patients with spinal cord injury (SCI).

Data sources The PubMed, Embase, Cochrane Library databases were systematically searched from inception until December 24, 2024.

Study selection Eligible randomized controlled trials contained information on the population (SCI), intervention (REGT), and outcomes (walking speed and distance, walking balance, functional scores for SCI rehabilitation, respiratory function). Participants in the REGT intervention group were compared with those in conventional physical gait training (CPT) groups. Two independent researchers conducted the research,screened the articles, and assessed their eligibility.

Data extraction Two independent researchers extracted key information from each eligible study. The authors' names, year of publication, setting, total sample size, REGT, CPT training schedule, baseline/mean difference (MD), and 95% confidence interval (CI) were extracted using a standardized form, and the methodological quality was assessed using the GRADE (Grading of Recommendations, Assessment, Development, and Evaluation) system.

Data synthesis Of 595 studies identified, 15 randomized controlled trials (n = 579) were included for meta-analysis. Compared with conventional physical gait training (CPT), REGT showed no significant efficacy in walking speed (10-Meter Walk Test, WMD (95%CI) = − 0.03 (− 0.06, 0.00) m/s, $P = 0.08$) and walking distance, (6-Minute Walk Test, WMD (95% CI) = -1.83 (− 14.48, 10.83) meters, $P = 0.78$). REGT showed statistically significant efficacy in walking stability (Timed Up and Go, WMD (95%CI) = 6.62 (0.35, 12.88) s, $P = 0.04$) and functional scores such as Walking Index for Spinal Cord Injury Version II (WMD (95%CI) = 2.17 (1.05, 3.29), $P = 0.0001$) and Lower Extremity Motor Score (WMD (95%CI) = 1.33 (0.58, 2.07), $P = 0.0005$). Additional Significant efficacy was also found in terms of respiratory function (forced expiratory volume in one second, WMD (95%CI) = 0.60 (0.05, 1.16) L, $P = 0.03$).

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Conclusions This meta-analysis discovered the evidence that robotic exoskeleton gait training can improve the walking balance, strength of lower limbs, functional scores and respiratory function in the patients with spinal cord injury (SCI) compared to conventional gait training (CPT). No obvious evidence showed that REGT has more advantages than CPT in improving walking speed and distance. REGT combined with CPT are more recommended in the discovery of walking speed and distance of patients above 6 months after SCI.

Keywords Robotic exoskeleton gait training, Spinal cord injury, Meta-analysis, Gait rehabilitation

Spinal cord injury (SCI) is a devastating type of injury that impairs the movement, sensation, and bowel and bladder functions of patients due to damage to the spinal cord. The incidence rate of non-traumatic SCI is higher than that of traumatic spinal cord injury (TSCI) in developed countries, with an annual TSCI incidence rate of 9.3 per million population [1]. China is a high-prevalence country for SCI, with over 3 million SCI patients, and the number of new cases each year is as high as 90,000 [2]. Manifestation of chronic spinal cord injury includes Paraplegia, Tetraplegia, and Loss of sensation, muscle strength. After SCI, there are various secondary health issues such as cardiovascular complications, respiratory system complications, gastrointestinal and bladder dysfunction, muscle atrophy, obesity, osteoporosis, and pressure sores, which seriously affect the survival situation and quality of patients' life, and may consequently reduce their life expectancy [3–7].

In the aftermath of SCI, patients often have to face a challenging and lengthy rehabilitation process. The outcomes of rehabilitation for chronic SCI can vary depending on the severity and level of injury lesion, as well as the overall health and well-being of the individuals. However, it is important to note that the prognosis for recovery may be limited, and many individuals with chronic SCI experience long-term physical and cognitive impairments. Previous recommendations for SCI patients have included aerobic training, upper limb strength training, and lower limb flexibility training to maintain or improve motor abilities [8]. For individuals with cervical injuries affecting respiratory muscles, respiratory muscle training is suggested [9]. Advancements in neuroscientific technology have led to the emergence of various techniques, such as lower limb robotic exoskeletons [10], unloading training systems, muscle functional electrical stimulation, epidural electrical stimulation [11], brain-machine interfaces [12], and spinal cord neuromodulation techniques. These techniques are gradually transitioning from the laboratory to clinical settings with the aim of preserving active movement during the training for patients [13, 14]. The development of robotic exoskeletons, initially conceptualized decades ago, has gained significant momentum over the past 10–15 years, [15]. Based on assistance intensity, exoskeletons are classified as passive, powered, or active [16]. Device complexity and assistance capacity further depend on the number of actuated joints (e.g., ankle, knee, hip, or trunk), with multi-joint systems (e.g., knee-ankle–foot exoskeletons) addressing severe mobility deficits by supporting entire lower limbs [17, 18].

Robotic exoskeletons gait training (REGT) have become a popular and innovative solution for individuals with SCI to aid in their rehabilitation process. The first exoskeleton devices were invented in the 1960s [19]. Some well-known manufacturers of exoskeleton devices include Ekso Bionics, Cyberdyne, and Rex Bionics [20–22]. Robotic exoskeletons are wearable devices designed to assist patients with SCI in standing up and walking [23]. They can be controlled through a remote control or by using sensors and algorithms, allowing the exoskeleton to respond to the patient's movements [24, 25]. Many robotic exoskeletons also have adjustable joint angles [26], which can help prevent falls and provide better support during rehabilitation. The Lokomat system is an exoskeleton apparatus that includes a robotic exoskeleton device and a treadmill equipped with multiple sensors and electric drives [27]. Actuator-powered exoskeletons offer a new approach to improving rehabilitation outcomes for patients with SCI as walking assistance devices [28]. Through continuous lower limb weight-bearing walking, REGT provides various sensory stimulations related to walking to the central nervous system, promoting the integration of different sensory inputs [29, 30]. This, in turn, enhances the function of the central pattern generator (CPG) in the spinal cord [31–33], strengthening the coordinated movement of agonist and antagonist muscles. Additionally, REGT promotes neuromuscular plasticity and facilitates the recovery of neural connectivity [34].

REGT has shown promising results in the field of rehabilitation for individuals with SCI. However, there is currently a lack of established guidelines or standardized practices for REGT in the treatment of SCI patients. Therefore, it is necessary to conduct a comprehensive assessment, both qualitative and quantitative, to evaluate the impact of REGT on patients with SCI, based on randomized controlled trials (RCTs). The objective of this meta-analysis is to systematically review and analyze the therapeutic efficacy of REGT in SCI patients, with the

aim of supporting SCI treatment and providing reliable recommendations for clinical practice.

Methods

Search strategy

In line with the PRISMA guidelines, the researchers conducted this study. This research protocol has been registered with the PROSPERO (CRD420251011718). A thorough exploration was performed on PubMed (1966-December 2024), Embase (1974-December 2024), and Cochrane Central Register of Controlled Trials (1991-December 2024) databases to identify pertinent literature pertaining to human studies published in the English language. The search strategy encompassed terms associated with spinal cord injury, exoskeletons, and the Lokomat. Specifically, we employed combinations of Medical Subject Headings (MeSH) terms and keywords, including "spinal cord injury," "exoskeleton," "Lokomat," and "robot-assisted." A comprehensive overview of the search strategy and the complete list of search terms can be found in Supplementary Tables S1–S3. We utilized the PICOS principle proposed by Cochrane, which encompasses the following components: population (spinal cord injury), intervention (exoskeleton, Lokomat, or robot-assisted gait training), comparison (conventional physical gait training), outcomes[Timed Up and Go (TUG) test, the Walking Index for Spinal Cord Injury Version II (WISCI-II), the Lower Extremity Motor Score (LEMS), as well as ground walking endurance such as the 6-Minute Walk Test (6 MWT) and the walking speed as the 10-Meter Walk Test (10 MWT), in addition to relevant respiratory function assessments] and study design (RCT). In addition, we conducted a manual search using references from the included studies to identify other potentially eligible studies, thereby enhancing the comprehensiveness of our search.

Inclusion and exclusion criteria

Two evaluators independently assessed the titles, abstracts, and complete texts of the articles. Only those studies that fulfilled the predefined inclusion criteria were considered for inclusion in the meta-analysis. The inclusion criteria for research on the impact of robotic exoskeleton gait training on mobility in patients with SCI were as follows: (1) The studies needed to involve a robotic exoskeleton, which refers to a multi-joint orthotic device that is fueled by an external source and has the capability of moving at least two joints on each leg. (2) Moreover, the inclusion criteria encompassed adult patients aged 18 years and above. (3) The studies were peer-reviewed full-text publications or articles in press. (4) The design type of the patient grouping included in the study is RCT. Other study designs such as non randomized controlled trials or pre-post studies or pilot studies were not included in this systematic review.

The following studies were not considered: (1) Studies involving a combination of robotic exoskeleton gait training with other treatments such as repetitive transcranial magnetic stimulation (rTMS); (2) Studies involving populations with multiple medical conditions (e.g., cerebral infarction and stroke) without distinct outcomes; (3) Studies with incomplete data; (4) Abstracts and conference summaries.

Data items

Data from each study were extracted by two reviewers independently using a predefined form for data extraction. Disputes were settled through discussion and, if needed, with the assistance of a third investigator. The extracted data included various variables, such as the walking index for spinal cord injury (WISCI-II), the lower extremity motor score (LEMS), the 6-minutes walk test (6 MWT), the 10-minutes walk test (10 MWT), the Timed Up and Go (TUG), as well as respiratory function measures like forced vital capacity (FVC), forced expiratory volume in 1 s (FEV1), and peak expiratory flow (PEF). In addition, we included demographic, clinical, and treatment characteristics in the extracted data. Furthermore, details concerning the type of intervention and control regimen, as well as the evaluation method, were also incorporated. If any of these variables were unavailable in a study, our strategy involved reaching out to the authors through email.

Quality assessment

The quality of the 15 studies included in this research was assessed by two reviewers, Fangyuan Chen and Jianqiao Yin, using the risk of bias (RoB) 1.0 evaluation framework developed by the Cochrane Collaboration. To determine bias, the reviewers examined random sequence generation, allocation concealment, blinding of participants and personnel, selective outcome assessment, incomplete outcome data, selective reporting, and other forms of bias.

The methodological quality of each selected trial was evaluated by obtaining scores from the PEDro website (www.pedro.org.au). In instances where information was unavailable, two researchers, Shengye Liu and Fangyuan Chen, conducted independent evaluations, with any disagreements resolved by the principal investigator, Liyu Yang. The PEDro scale is employed to assess the reliability and validity of randomized controlled trials (RCTs), utilizing a checklist comprising 11 evaluation items [35]. The PEDro score for each selected study serves as an indicator of methodological quality, categorized as follows: 9–10 indicates excellent quality, 6–8 indicates good

quality, 4–5 indicates fair quality, and scores below 4 indicate poor quality. Studies rated as good or excellent on the PEDro scale, with a sample size exceeding 50, are classified as providing level-1 evidence, whereas studies of lower quality, characterized by a fair or poor PEDro score and a sample size of 50 or fewer, are classified as providing level-2 evidence.

The level of evidence was classified using the GRADE (Grading of Recommendations, Assessment, Development, and Evaluation) system, which categorizes evidence as high, moderate, low, or very low. Any disagreements were resolved through consensus reached via discussion. The assessment was conducted using the RevMan 5.3 software, which was provided by The Cochrane Collaboration located in London, United Kingdom.

Statistical analysis

A scientific investigation was undertaken to evaluate the efficacy of therapy in improving the walking ability of patients. To ascertain the outcome, multiple measures such as WISCI-II, LEMS, TUG, 6MWT, and 10 MWT were employed. The outcomes were presented as the weighted mean difference (WMD), while 95% confidence intervals (CIs) were calculated using the inverse variance technique, considering random effect weighting. To merge the data obtained from various studies, the change value for each outcome was pooled. The power of individual reports included in the present meta-analysis was accessed by GPower software v.3.1. To assess heterogeneity among the studies, the Cochran's Q test and the I^2 statistic were utilized. A significant heterogeneity was considered when $I^2 \geq 50\%$. Upon investigating the sources of heterogeneity, subgroup analyses were performed based on the type of robotic training, which included Lokomat and exoskeleton, and the starting time of gait training after SCI (within 6 months or above). All statistical analyses were carried out using RevMan version 5.3.

Result

Literature search process results

During the database search, a total of 595 articles were identified. After excluding 228 duplicate references, a total of 367 articles remain for further review. To ensure the relevance and appropriateness of the studies, we screened the titles and abstracts, resulting in the exclusion of 345 irrelevant studies. Subsequently, we thoroughly examined the main texts of the remaining articles and engaged in a collaborative effort between two independent reviewers. This led to the discussion of 22 studies. Among these, 7 publications were considered unsuitable and were excluded. Ultimately, a total of 15 studies met the criteria for inclusion in the meta-analysis. For a visual representation of the literature screening process, please refer to Fig. 1.

Study characteristics

The characteristics of the included studies are shown in Table 1. The included studies were conducted between 2011 and 2024 across six countries worldwide. The spinal cord injury levels of participants ranged from ASIA A to D. In these studies, the ages of patients in the combined treatment group varied from 26 to 71 years, with the average time since the onset of spinal cord injury ranging from 2 months to 15 years (Table 1). The treatment frequency varied from 2 to 5 times per week, while the duration of gait training ranged from 3 to 20 weeks, training details shown in the Table 2.

Risk of bias in the included studies

Figure 2 illustrates the risks of bias encountered in the included studies. It is noteworthy that almost all of the studies in the sample showed minimal bias risk in terms of random sequence generation and allocation concealment, except for Shin et al. [36]. However, all the studies demonstrated a bias risk in relation to participant and personnel blinding. On the other hand, every single study depicted a low or moderate bias risk in terms of outcome assessment blinding, incomplete outcome data, and selective reporting. The evaluation results of the PEDro scale show that the methodological quality of 5 articles is Fair, while the remaining studies are Good (Table 3). Only 2 articles are Level-1 evidence, and the rest are Level-2 evidence. The GRADE evaluation results indicate that the evidence level for the 10 MWT is "Moderate" the evidence level for the 6MWT is "Very Low", and the other outcome indicators are all "Low". (Table S4)

Results of individual studies

10 MWT meta-analysis results

In the research conducted, a total of 218 participants were involved in nine different studies. The 10 MWT test was examined, and based on the heterogeneity test results ($I^2 = 2\%$, $P = 0.43$), a fixed effect model was used to analyze the collected data. The analysis indicated that there were no significant improvements observed in SCI patients who underwent robotic exoskeleton gait training compared to those who received conventional physiotherapy (CPT). The results can be seen in Fig. 3A, and the analysis outcomes [WMD (95%CI) = − 0.03 (− 0.06, 0.00) m/s, $P = 0.08$] support this conclusion.

6MWT meta-analysis results

A total of 116 participants were involved in six separate studies examining the 6-min walk test (6MWT). A fixed effect model was used to determine the statistical

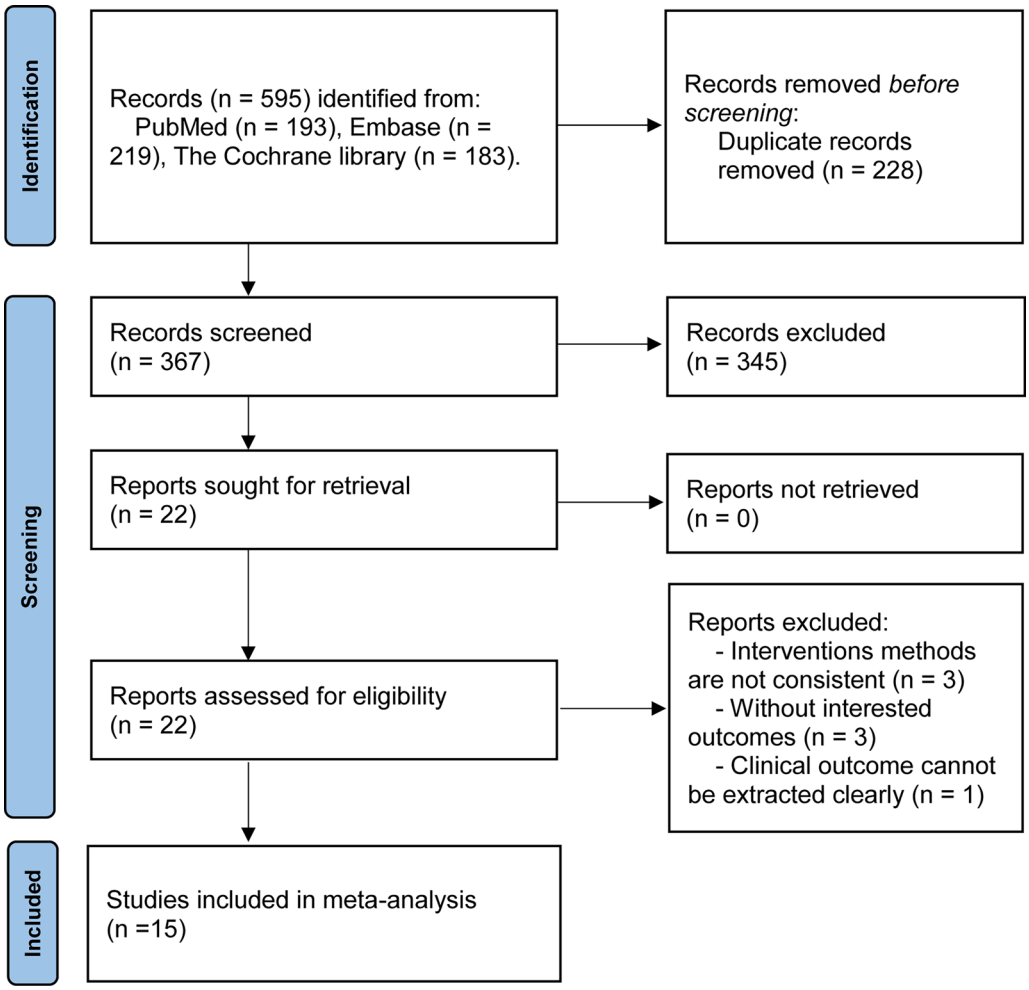

Fig. 1 Flow chart showing the study selection process

heterogeneity (I^2 = 32%, P = 0.18). The analysis findings showed no significant difference in improving walking stamina between REGT and conventional physical therapy (CPT) [WMD (95% CI) = − 1.83 (− 14.48, 10.83) meters, P = 0.78], as shown in Fig. 3B.

For the purpose of exploring more result details, we carried out subgroup analyses considering the duration of injury as well as the type of robotic physical therapy. An examination of the 10 MWT subgroup indicated the following outcomes: ① Within a duration of 6 months, the WMD (95%CI) was 0.07 (− 0.03, 0.17) m/s, P = 0.17; ② Beyond 6 months, the WMD (95%CI) was − 0.04 (− 0.07, − 0.01) m/s, P = 0.02 (Fig. 4A). Regarding the 6MWT subgroup, we observed: ① Duration less than 6 months, the WMD (95% CI) was 31.8 (− 3.21, 66.81) meters, P = 0.08; ② Beyond 6 months, the WMD (95%CI) was − 6.88 (− 20.45, 6.69) meters, P = 0.32 (Fig. 4B). These findings demonstrate that conventional physical therapy(CPT) exhibited a significantly superior impact on improving walking speed (10MWT) for individuals with an injury duration surpassing 6 months when compared to robotic exoskeleton gait training (REGT), as demonstrated in Fig. 4A. The subgroup analysis concerning different types of robotic training is outlined below: 10 MWT exhibited: ① Employment of Lokomat yielded a WMD (95%CI) of − 0.04 (− 0.07, − 0.01) m/s, P = 0.02; ② Employment of exoskeleton resulted in a WMD (95%CI) of 0.05 (− 0.06, 0.12) m/s, P = 0.25 (Fig. 4C). With respect to 6MWT: ① Utilization of Lokomat produced a WMD (95% CI) of − 9.29 (− 25.16, 6.57) meters, P = 0.25; ② Utilization of exoskeleton yielded a WMD (95%CI) of 11.22 (− 9.75, 32.20) meters, P = 0.29 (Fig. 4D). These results indicate that Lokomat robotic training was less effective in enhancing walking speed (10 MWT) compared to CPT, as presented in Fig. 4C.

Table 1 Characteristics of included studies

Study	Country	Design of Trial	Robotic gait training	AISA classification	Duration of injury	Groups	Sample size for randomized	Withdraw, case (%)	Sample size included in the analysis, M/F	Age, years	Outcomes
Alcobendas-Maestro, M. 2012	Spain	RCT	Lokomat	C or D	120 (87.5–145) days	REGT	40	3 (7.5)	37, 23/14	45.2 ± 15.5	WISCI-II, 6 MWT, FIM, LEMS
					135 (93.7–180) days	CPT	40	2 (5)	38, 24/14	49.5 ± 12.8	
Chang, S. 2018	USA	RCT	Ekso exoskeleton	C or D	15 ± 14 years	REGT	4	0 (0)	4, 3/1	56 ± 17	10 MWT, 6 MWT, TUG, LEMS
					7 ± 3 years	CPT	5	2 (40)	3, 2/1	60±2	
Cheung, EYY 2019	China	RCT	Lokomat	B, C or D	17.0 ± 7.01 months	REGT	8	0 (0)	8, 7/1	55.6 ± 4.98	WISCI-II, SCIM-III, FVC, PEF, FEV1
					10.4 ± 6.31 months	CPT	8	0 (0)	8, 4/4	53.0 ± 12.94	
Cinar, C. 2021	Turkey	RCT	Lokomat	A	3.5 ± 2.1 months	REGT	20	3 (15)	17, 7/10	32.9 ± 11.4	WISCI-II, FIM
					3.8 ± 2.6 months	CPT	20	0 (0)	20, 8/12	36.9 ± 12.6	
Edwards, D. 2022	USA	RCT	Ekso exoskeleton	C or D	1.2–28.5 years	REGT	14	2 (14.3)	12, 5/7	26–58	10 MWT, 6 MWT, TUG, WISCI-II
					2.1–14.2 years	CPT	13	1 (7.7)	12, 6/6	28–71	
Esclarin-Ruz, A. 2014	Spain	RCT	Lokomat	C or D	125.6 ± 65.2 days	REGT (a)	22	1 (4.5)	21, 15/6	43.6 ± 12	6 MWT, WISCI-II, LEMS
					140.3 ± 45.5 days	CPT (a)	22	1 (4.5)	21, 13/8	44.9 ± 7	
					117.9 ± 25.6 days	REGT (b)	22	2 (9.1)	20, 14/6	36.4 ± 12	
					109 ± 50.5 days	CPT (b)	22	1 (4.5)	21, 17/4	42.7 ± 18	
Field-Fote, E. C. 2011	USA	RCT	Lokomat	C or D	≥ 1 year	REGT	15	1 (6.7)	14, 12/2	45 ± 8.0	10 MWT, LEMS
						CPT1	18	3 (16.7)	15, 11/4	42.2 ± 15.7	
						CPT2	22	4 (18.2)	18, 16/2	38.5 ± 12.7	
						CPT3	19	2 (10.5)	17, 14/3	39.3 ± 14.6	
GilAgudo, A. 2023	Spain	RCT	HANK exoskeleton	C or D	4.82 ± 1.3 months	REGT	12	1 (8.3)	11, 7/4	41 ± 12.39	10 MWT, 6 MWT, TUG, WISCI-II
					5.55 ± 2.3 months	CPT	11	1 (9.1)	10, 8/2	51.8 ± 11.93	
Midik, M. 2020	Turkey	RCT	Lokomat	C or D	5 (4–30) months	REGT	15	0 (0)	15, 15/0	35.4 ± 12.1	LEMS, WISCI-II, SCIM-III
					27 (17–44) months	CPT	15	0 (0)	15, 15/0	37.9 ± 10.0	
PIIRA, A. 2019	Norway	RCT	Lokomat	C or D	8 (2–54) years	REGT	12	5 (41.7)	7, 4/3	55 ± 8	10 MWT, 6 MWT, LEMS
					7 (2–48) years	CPT	12	0 (0)	12, 5/7	46 ± 15	
Shin, J. C. 2014	Korea	RCT	Lokomat	D	3.33 ± 2.02 months	REGT	30	3 (10)	27, 20/7	43.15 ± 14.37	LEMS, WISCI-II, SCIM-III
					2.73 ± 1.97 months	CPT	30	4 (13.3)	26, 14/12	48.15 ± 11.49	
Tsai, C. 2024	USA	RCT	Ekso exoskeleton	A, B, or C	< 3 months	REGT	20	4 (20)	16, 10/6	45.8 ± 18.3	LEMS
						CPT	12	0 (0)	12, 9/3	46.8 ± 18.3	
Wu, M. 2018	USA	RCT	Lokomat	C or D	7 (1–8) years	RGT	8	1 (12.5)	8, 7/1	45 (26–63)	10 MWT, 6 MWT
					6 (1–24) years	CPT	8	1 (12.5)	8, 5/3	48 (40–54)	

Table 1 (continued)

Study	Country	Design of Trial	Robotic gait training	AISA classification	Duration of injury	Groups	Sample size for randomized	Withdraw, case (%)	Sample size included in the analysis, M/F	Age, years	Outcomes
Xiang, X 2021	China	RCT	Ekso exoskeleton	A, B, or C	2.0 ± 4.5 months	REGT	9	1 (11.1)	9, 2/7	39.8 ± 12.2	6 MWT, LEMS, PEF, FVC, FEV1
					2.0 ± 0.5 months	CPT	9	1 (11.1)	9, 1/8	36.6 ± 11.8	
Yildirim, M. 2019	Turkey	RCT	Ekso exoskeleton	A, B, C, D	3 ± 2 months	REGT	46	2 (4.3)	44, 17/27	32 ± 23	WISCI-II, FIM
						CPT	47	3 (6.4)	44, 16/28	36.5 ± 24	

Abbreviations: RCT, randomized control trial; 10-metre walk test, 10 MWT; 6-minute walk test, 6 MWT; Walking Index for Spinal Cord Injury II, WISCI-II; Time up to go, TUG; Functional Independence Measure, FIM; Lower Extremity Motor Scores, LEMS; Spinal Cord Independence Measure version III, FVC; Peak expiratory flow, PEF; Forced expiratory volume in one second, FEV1; a, patients with Upper Motor Neuron Lesions; b, patients with Lower Motor Neuron Lesions

Table 2 Training details of included studies

Study	Groups	Training	Cycle
Alcobendas-Maestro, M. 2012	REGT	60 min/day (30-min overground therapy for walking, 30-min with the Lokomat)	5 days/week for 8 weeks
	CPT	Walking training sessions of 1 hour/day	
Chang, S. 2018	REGT	Included sit to stand, static and dynamic standing balance, weight shifting, walking, turning, and stand to sit	60 min/day, 5 days/week for 3 weeks
	CPT	Stretching, strengthening, balance training, standing, sit to stand, stair, and gait training	
Cheung, E. Y. Y. 2019	REGT	CPT + Robotic-assisted body weight supported treadmill training, 30 min/day, 3 days/week	8 weeks
	CPT	One hour of standard physiotherapy program, twice per week	
Cinar, C. 2021	REGT	CPT + Robotic therapy training, Twice a week	8 weeks
	CPT	Conventional treatment once a day, 5 days a week	
Edwards, D. 2022	REGT	45 min/day (30 min gait training in the Ekso, followed by 15min performing standard overground (OG) gait training outside the Ekso)	3 days/week for 12 weeks
	CPT	45 min of Body Weight Supported (BWS) Treadmill Training, and if possible, OG training without BWS	
Esclarin-Ruz, A. 2014	REGT	60 min/day (30 minutes of conventional mobility training plus 30 minutes of robotic-assisted mobility training),	5 days/week for 8 weeks
	CPT	60 minutes of conventional mobility training	
Field-Fote, E. C. 2011	REGT	Treadmill-based training with robotic assistance	5 days/week, 12 weeks
	CPT1	Overground training with stimulation	
	CPT2	Treadmill based training with stimulation	
	CPT3	Treadmill based training with manual assistance	
GilAgudo, A. 2023	REGT	Robotic ambulatory gait training sessions, 30 min/day	3 days/week for 5 weeks
	CPT	Traditional gait training program (analytical mobilization, strengthening exercises for the lower limbs and gait re-education when possibleusing parallels)	
Hu, X. M. 2024	REGT	CPT + 40-50 minutes REGT (including sitting, standing and walking training), once a day, five times a week	8 weeks
	CPT	Routine exercise therapy	
Midik, M. 2020	REGT	CPT + REGT, 30 min/day, 3 days/week	5 weeks
	CPT	Regular physiotherapy for five times a week	
PIIRA, A. 2019	REGT	40-90 min/day (stepping on a treadmill with body-weight support, Overground walking and/or exercises on the treadmill), 3 days/week	20 weeks
	CPT	Low-intensity usual care from their local physical therapist, usually 1-5 times per week	
Shin, J. C. 2014	REGT	REGT (40 min) + regular treatment (30 min), 3 days/week, and 2 days with regular treatment (60 min/day) a week	4 weeks
	CPT	Twice a day in a 30-minute session, 5 times a week	
Tsai, C. 2024	REGT	Overground walking utilizing a powered exoskeleton, 15 hours per week	7 weeks
	CPT	Incorporating walking with the use of parallel bars, a treadmill with an overhead lift, and ceiling track, or a body-weight support device on wheels, 15 hours per week	
Wu, M. 2018	RGT	Robotic treadmill training or Overground walking practice 45 min/day, 3 days/week	6 weeks
	CPT	Treadmill training or Overground walking practice	
Xiang, X. 2021	REGT	Exoskeleton-assisted walking training program (standing, leaning on the wall, or sitting)	50-60 min/day, 4 days/week, 4 weeks
	CPT	Strength training using dumbbell between 5 and 20 kg, aerobic exercise, such as walking training with brace as well as static and dynamic balance training in sitting or standing position	
Yildirim, M. 2019	REGT	CPT + Robotic therapy training 30 min/day, 2 days/week	8 weeks
	CPT	Conventional therapy (joint range of motion, stretching, strengthening and gait training), 5 days a week (twice a day)	

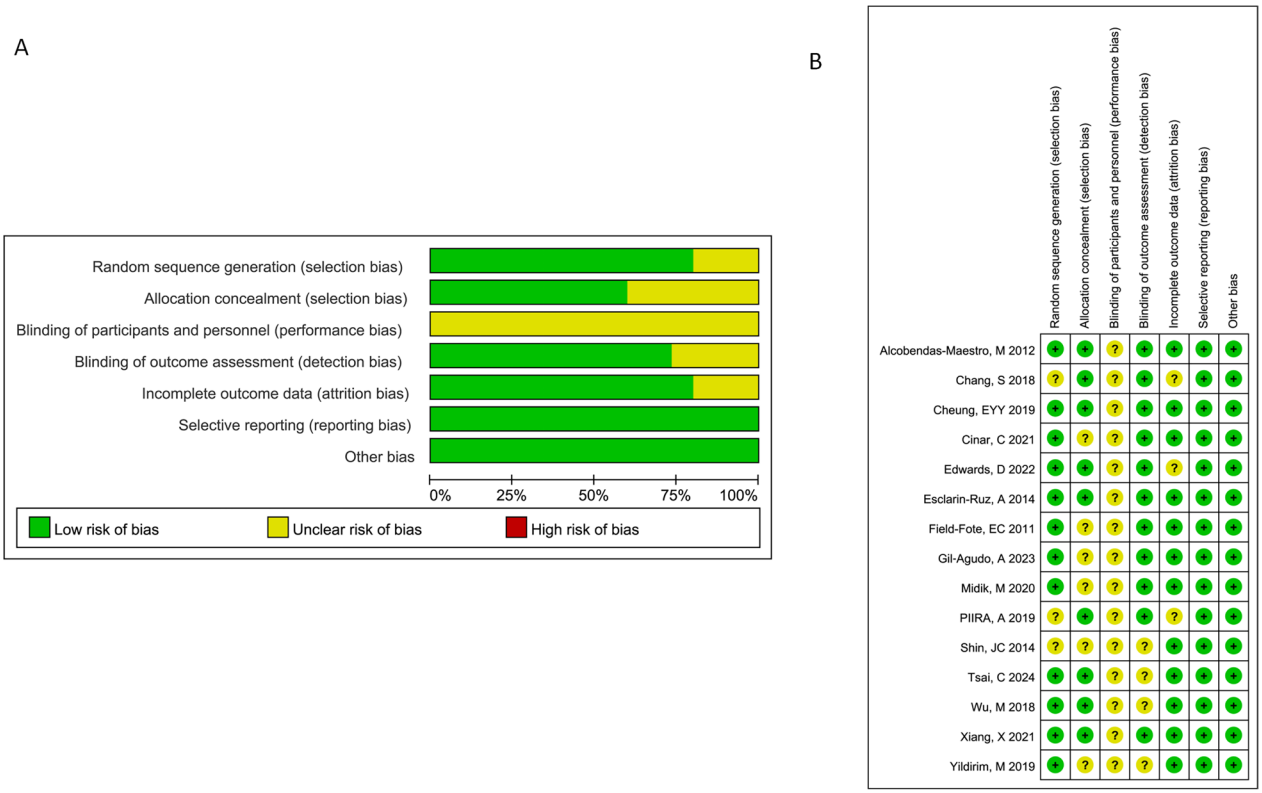

Fig. 2 Risk of bias graph and summary

TUG meta-analysis results

The investigation of the Timed Up and Go (TUG) test consists of two separate studies with a total of 28 participants. In order to assess the heterogeneity, a test was conducted which revealed an I^2 value of 0% and a *P*-value of 0.65. As a result, a fixed effects model was chosen for further analysis. The results of the analysis indicated a statistically significant enhancement in TUG for individuals with SCI who received REGT, with a (WMD) (95%CI) of 6.62 (0.35, 12.88) seconds and a *P*-value of 0.04. The visualization of these findings can be observed in Fig. 5A.

WISCI-II meta-analysis results

Eight studies involving a total of 403 subjects were conducted to examine the effectiveness of the WISCI-II in patients with SCI. To analyze the results, a random effects model was utilized, considering the heterogeneity test ($I^2=58\%$, $P=0.01$). The findings indicated that robotic exoskeleton gait training had a significant impact on improving the WISCI-II in SCI patients when compared to CPT. This conclusion was derived from the analysis results [WMD (95%CI) = 2.17 (1.05, 3.29), $P=0.0001$], as shown in Fig. 5B.

LEMS meta-analysis results

In total, 423 subjects participated in 11 separate studies that examined LEMS. When analyzing the data, a fixed effect model was utilized, taking into consideration the heterogeneity test ($I^2=0\%$, $P=0.59$). Findings from the analysis indicated a significant improvement in LEMS among SCI patients who underwent REGT, as compared to those who received CPT. This improvement was statistically significant [WMD (95%CI) = 1.33 (0.58, 2.07), $P=0.0005$], as demonstrated in Fig. 5C.

A subgroup analysis was conducted in the meta-analysis results of WISCI-II and LEMS, based on the duration of injury and the type of robotic physical therapy. The analysis of the WISCI-II subgroup revealed the following outcomes: ① Within a 6-month period, the weighted mean difference (WMD) (95%CI) was 2.52 (0.89, 4.15), $P=0.002$; ② Beyond 6 months, the WMD (95%CI) was 1.40 (0.93, 1.88), with statistical significance at $P<0.00001$ (Fig. 6A). In regard to the LEMS subgroup, the results were as follows: ① For less than 6 months in duration, the WMD (95% CI) was 2.76 (0.66, 4.86), approaching significance at $P=0.01$; ② Beyond 6 months, the WMD (95%CI) was 1.12 (0.32, 1.92), achieving statistical significance at $P=0.006$ (Fig. 6B). These subgroup findings demonstrate that REGT can enhance the functional

Table 3 The assessment of PEDro quality scores of the included RCTs

Study	Eligibility criteria	Random allocation	Concealed allocation	Baseline comparability	Blinded subjects	Blinded therapists	Blinded assessors	Adequate follow-up (> 85%)	Intention-to-treat analysis	Between-group comparisons	Point estimates and variability	Total PEDro score	Sample size ≥ 50	Level of evidence
Alcobendas-Maestro, M. 2012	Yes	1	1	1	0	0	1	1	1	1	1	8	Yes	1
Chang, S. 2018	Yes	0	1	1	0	0	1	1	0	0	1	5	No	2
Cheung, EYY 2019	Yes	1	1	1	0	0	1	1	1	1	1	8	No	2
Cinar, C. 2021	Yes	1	0	1	0	0	1	1	0	1	1	6	No	2
Edwards, D. 2022	Yes	1	1	1	0	0	1	0	0	1	1	6	No	2
Esclarin-Ruz, A. 2014	Yes	1	1	1	0	0	1	1	1	1	1	8	Yes	1
Field-Fote, E. C. 2011	Yes	1	0	1	0	0	1	1	0	1	1	6	Yes	2
GilAgudo, A. 2023	Yes	1	0	1	0	0	1	1	0	1	1	6	No	2
Midik, M 2020	Yes	1	0	1	0	0	1	1	0	1	1	6	No	2
PIIRA, A. 2019	Yes	0	1	1	0	0	1	0	0	1	1	5	No	2
Shin, J. C. 2014	Yes	0	0	1	0	0	0	1	0	1	1	4	Yes	2
Tsai, C. 2024	Yes	0	0	1	0	0	0	1	0	1	1	4	No	2
Wu, M. 2018	Yes	1	1	1	0	0	0	1	0	1	1	6	No	2
Xiang, X. 2021	Yes	1	1	1	0	0	1	1	1	1	1	8	No	2
Yildirim, M. 2019	Yes	1	0	1	0	0	0	1	0	1	1	5	Yes	2

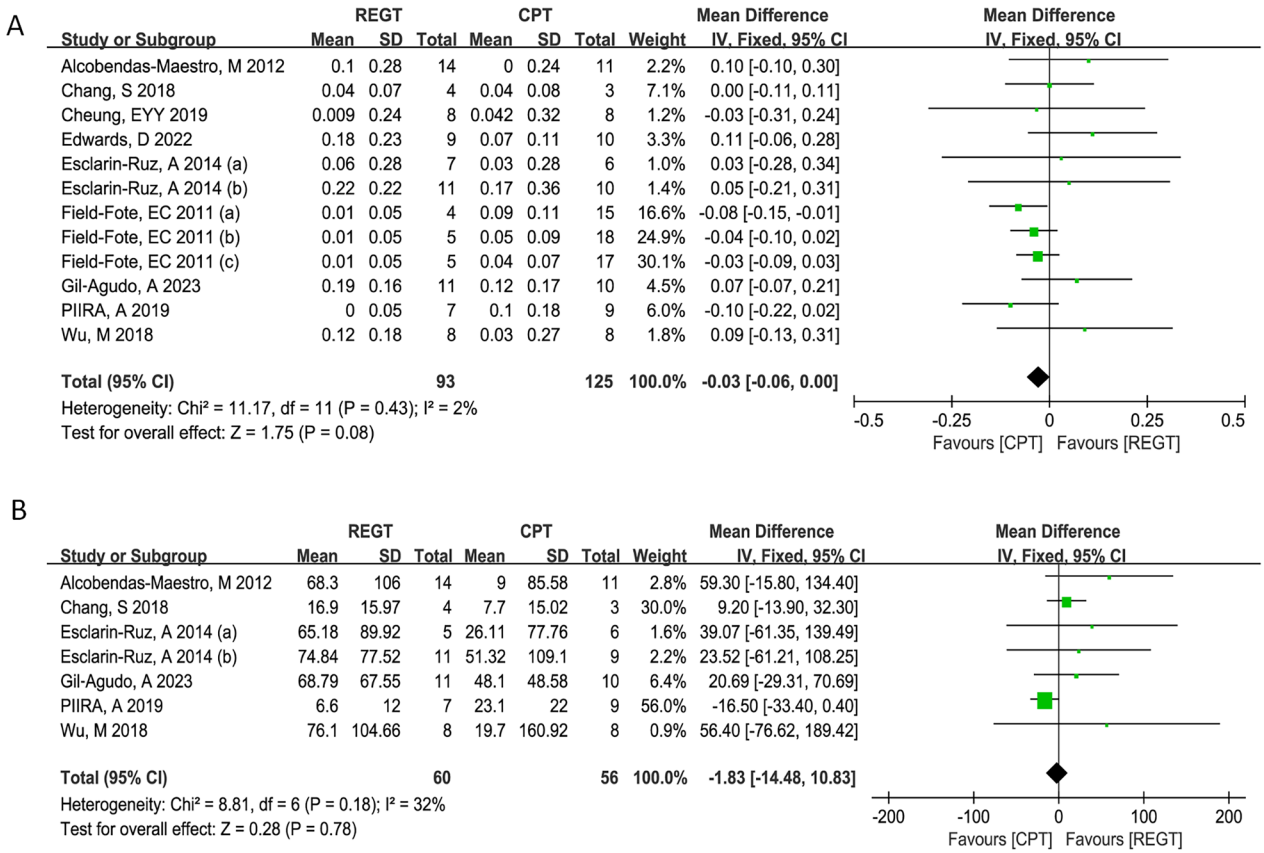

Fig. 3 Forest plots for REGT compared with CPT in walking speed assessing the 10 MWT (**A**), and walking distance using 6 MWT (**B**)

scores of patients with spinal cord injuries (WISCI-II and LEMS) whether the rehabilitation training starts within 6 months of SCI or more than 6 months. The subgroup analysis for different types of robotic training is outlined below: WISCI-II showed the following results: ① Lokomat exhibited a WMD (95%CI) of 2.05 (0.63, 3.47), with statistical significance at $P=0.005$; ② Exoskeleton resulted in a WMD (95%CI) of 2.75 (1.19, 4.30), with statistical significance at $P=0.0005$ (Fig. 6C). As for LEMS: ① The utilization of Lokomat produced a WMD (95% CI) of 1.22 (0.45, 1.99), with statistical significance at $P=0.002$; ② The utilization of exoskeleton yielded a WMD (95%CI) of 2.88 (− 0.11, 5.87) meters, with no significant effect at $P=0.06$ (Fig. 6D). These results indicate that Lokomat robotic gait training was significantly more effective in enhancing functional scores compared to exoskeleton in WISCI-II and LEMS, although exoskeleton also improved the WISCI-II scores as presented in Fig. 6C.

Respiratory function meta-analysis results

In two studies examining the effects of gait training assisted by a robotic exoskeleton on respiratory outcomes, including FVC, FEV1, and PEF, a total of 34 patients were analyzed. The fixed effect model was used in all three meta-analyses conducted in Fig. 7. The results indicated that gait training with a robotic exoskeleton significantly increased FEV1, but did not show significant improvements in FVC and PEF. Specifically, the findings revealed that there was a noteworthy increase in FEV1 [WMD (95%CI) = 0.60 (0.05, 1.16) L, $P=0.03$]. However, there was no significant improvement in FVC [WMD (95%CI) = 0.52 (− 0.17, 1.21) L, $P=0.14$] and PEF [WMD (95%CI) = 0.82 (− 0.62, 2.26) L, $P=0.27$]. Therefore, based on the analysis of these studies, it can be concluded that gait training with a robotic exoskeleton has a positive impact on FEV1 but does not significantly affect FVC and PEF.

Power analysis

The power of each included study and effect value for each outcome indicator can be found in Tables S5–S10. For the WISCI II and LEMS outcome measures, the power exceeds 0.80, indicating significant differences between the groups. In contrast, the power for the remaining outcome indicators is relatively low.

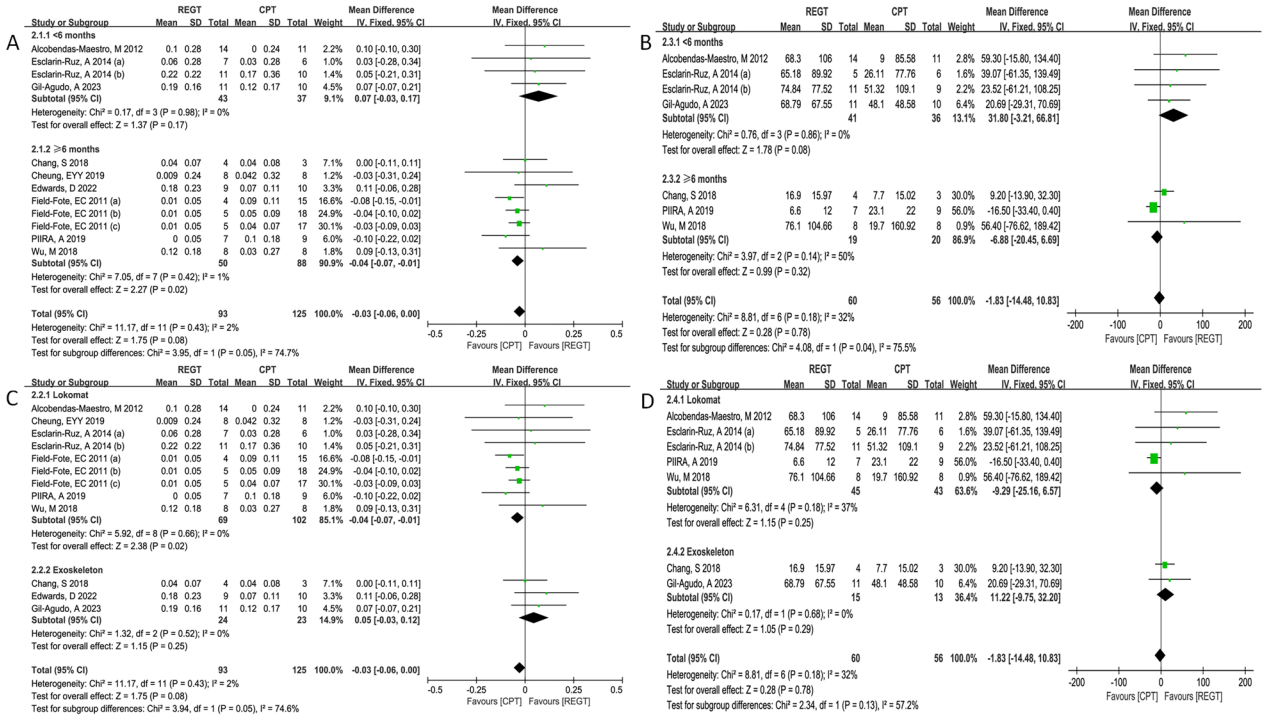

Fig. 4 Subgroup analysis of 10 MWT and 6 MWT. SCI patients were treated by REGT compared with CPT starting at the early stage or above 6 months after SCI assessing 10 MWT (**A**) and 6 MWT (**B**); utilizing different kind of robotic exoskeleton, Lokomat or exoskeleton assessing 10 MWT (**C**) and 6 MWT (**D**)

Discussion

This meta-analysis aims to explore the effectiveness of lower limb robotic exoskeletons in rehabilitation training for patients with SCI. Our meta-analysis results indicate that REGT intervention can better regulate the balance of patients with spinal cord injury compared to CPT. The post-injury walking motor function scores of patients, including TUG, WISCI-II and LEMS, showed significant improvement, and the FEV1 index of respiratory function was significantly enhanced. When analyzing the walking speed (10 MWT) and walking distance (6 MWT) results of rehabilitation training for patients with spinal cord injury, there was no significant difference between the REGT and CPT groups, indicating that the results were equivalent. In subgroup analysis, it was found that patients who began robotic exoskeleton gait training within 6 months after spinal cord injury did not show a significant difference in walking speed and distance compared to those who underwent traditional physical therapy. However, for patients with chronic spinal cord injury who started rehabilitation training after 6 months, conventional physical therapy was found to be more beneficial in improving walking speed. These results suggests that REGT can enhance the recovery of walking balance, muscle strength of lower limbs, and pulmonary function in patients with spinal cord injury. In terms of motor function recovery of SCI patients, robotic exoskeleton-assisted training may be considered, while we recommend combining REGT with CPT to better improve the walking speed recovery in patients with spinal cord injuries in the medium to long term.

Through the results of meta-analysis, we have found that REGT does not have a significant effect on improving patients' walking speed compared to CPT. What is even more surprising is that CPT has greater advantages for patients' walking speed with spinal cord injuries over 6 months. However, for patients injured within 6 months, REGT has the same effect as CPT. Combining the improvement results of REGT on gait and SCI-related scores, we conclude that for patients with diagnosis of SCI (Injury within 6 months), both REGT and CPT can improve the patient's walking speed and distance. Moreover, REGT can also enhance strength of lower limbs and walking balance. For the length of complication duration above 6 months after SCI, it is recommended to consider traditional treatment methods or a combination of robotic exoskeletons and traditional rehabilitation approaches. The 10-m walk test (10MWT) is primarily used to measure the fastest speed at which a 10-m walk can be completed. A result of less than 0.94m/s often indicates a lack of walking ability [37]. Traditional upright walking transfer training poses significant challenges for

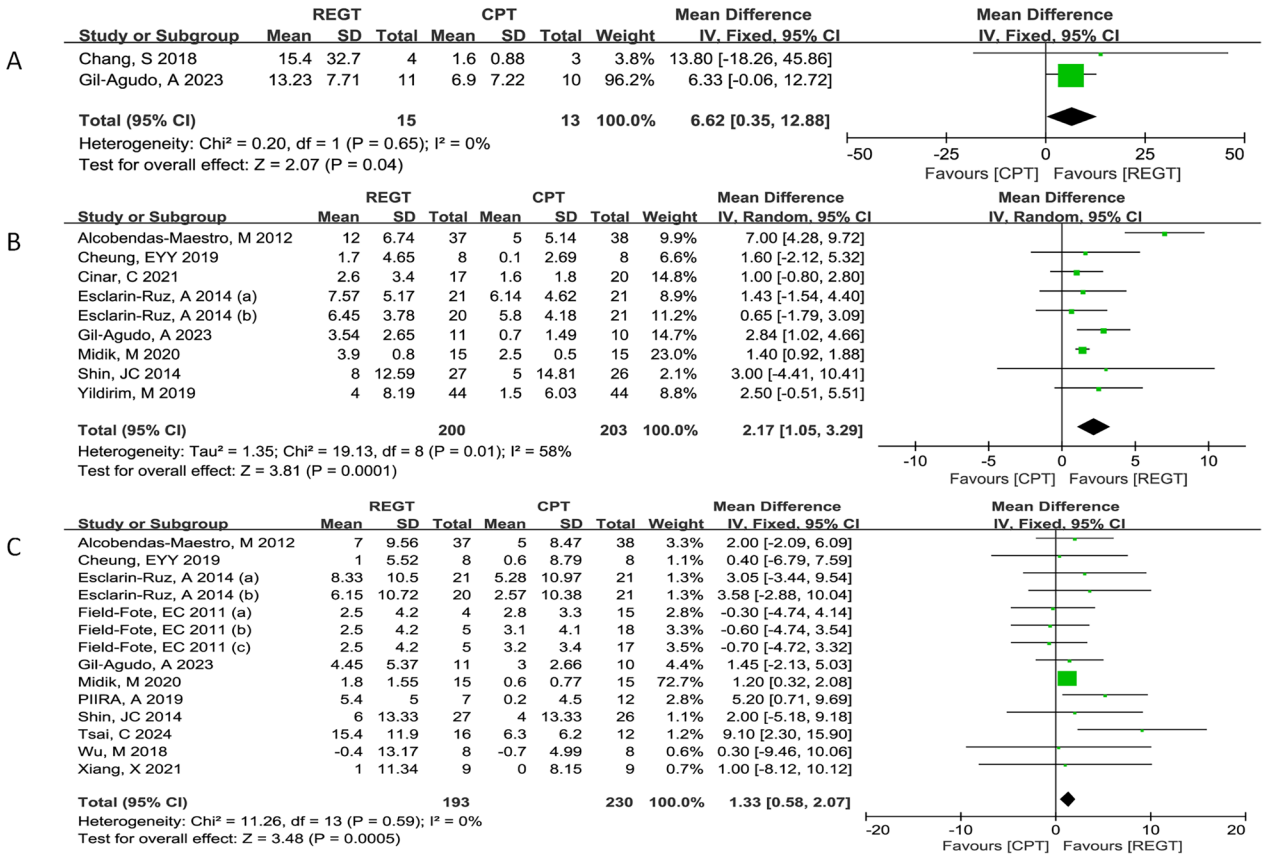

Fig. 5 Forest plots for REGT compared with CPT in walking stability assessing TUG (**A**) and functional scores using the WISCI-II (**B**) and LEMS (**C**)

both patients and therapists in the early stages of spinal cord injury. In order to maintain an upright position, it usually requires the assistance of at least two therapists and sometimes the cooperation of family members, making the training inconvenient. The emergence of REGT addresses these limitations. REGT simulates the physiological walking mode and provides body weight support, freeing the therapist's hands. This makes early upright walking transfer training for spinal cord injuries easier to implement. Existing research suggests that nerves exhibit stronger self-repair ability and plasticity in the early stages of injury [38–40], allowing patients to receive more physiological walking transfer training during this period. This may enable nerve remodeling according to our expectations of the desired pattern. For patients with spinal cord injuries lasting longer than 6 months, additional physical stimulation and training may be necessary.

According to the results of a meta-analysis, REGT has been found to improve the walking balance of patients with spinal cord injury. The Timed Up and Go (TUG) test is commonly used to evaluate the overall multi-task mobility score [41]. The analysis revealed that REGT had a significantly higher score than CPT in this test, indicating that REGT improves the patient's center of gravity shift and overall balance after robotic exoskeleton training, leading to improved walking balance. Recent research [42] also suggests that actively controlling the abnormal swing of the trunk core can effectively enhance the movement balance of patients with spinal cord injuries, who often face difficulties in walking. Patients with SCI face difficulties in controlling sideways movement during walking, which makes it challenging to position the foot in the mediolateral direction [43]. Additionally, they experience limitations in expanding their stability boundaries after being disturbed, and it requires significant metabolic energy to stabilize sideways motion while walking [44]. In comparison to adults of the same age without spinal cord injury, patients who do not use assistive devices exhibit greater lateral deflection of the center of mass when walking at higher speeds [45]. In the field of training using robotic exoskeletons, patients with spinal cord injuries can reduce the abnormal swing of the body's trunk, thereby providing a more stable foothold for walking [46]. This helps in reducing the swing of the trunk core in the sagittal plane and lessens the need for patients to exert energy and psychological stress in

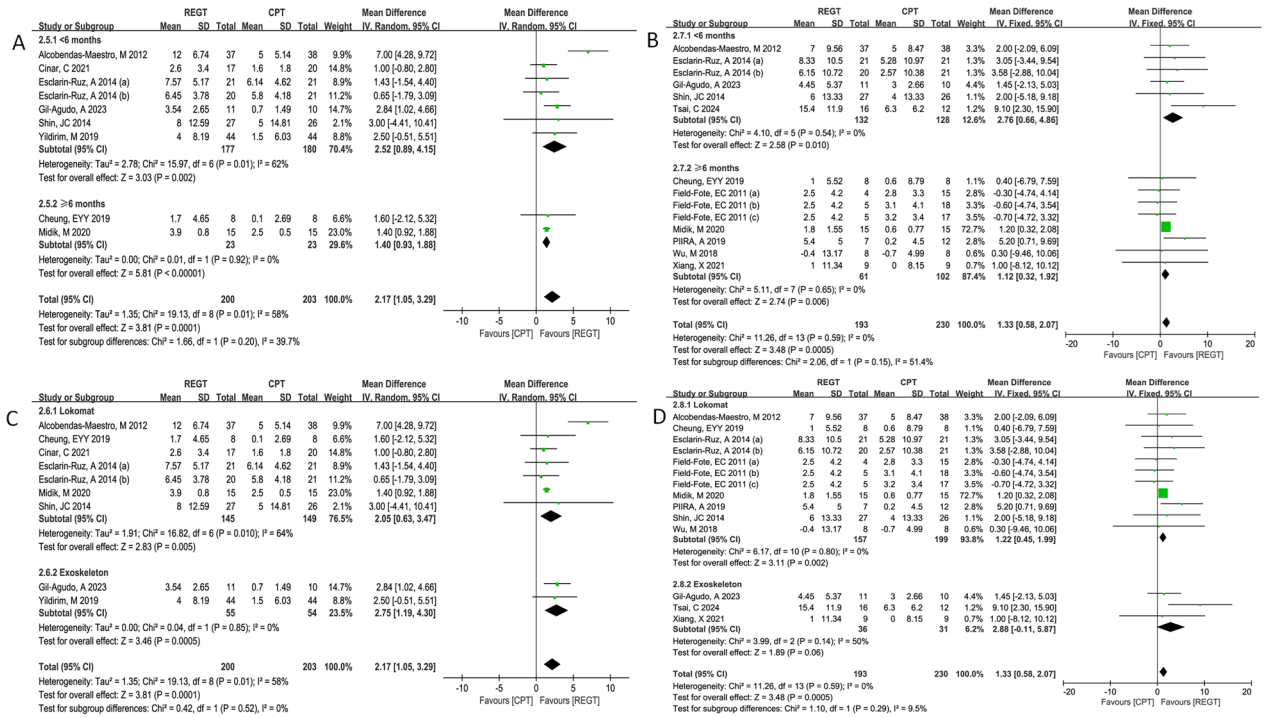

Fig. 6 Subgroup analysis of WISCI-II and LEMS. SCI patients were treated by REGT compared with CPT starting at the early stage or 6 months after SCI assessing WISCI-II (**A**) and LEMS (**B**); utilizing different kind of robotic exoskeleton, Lokomat or exoskeleton assessing WISCI-II (**C**) and LEMS (**D**)

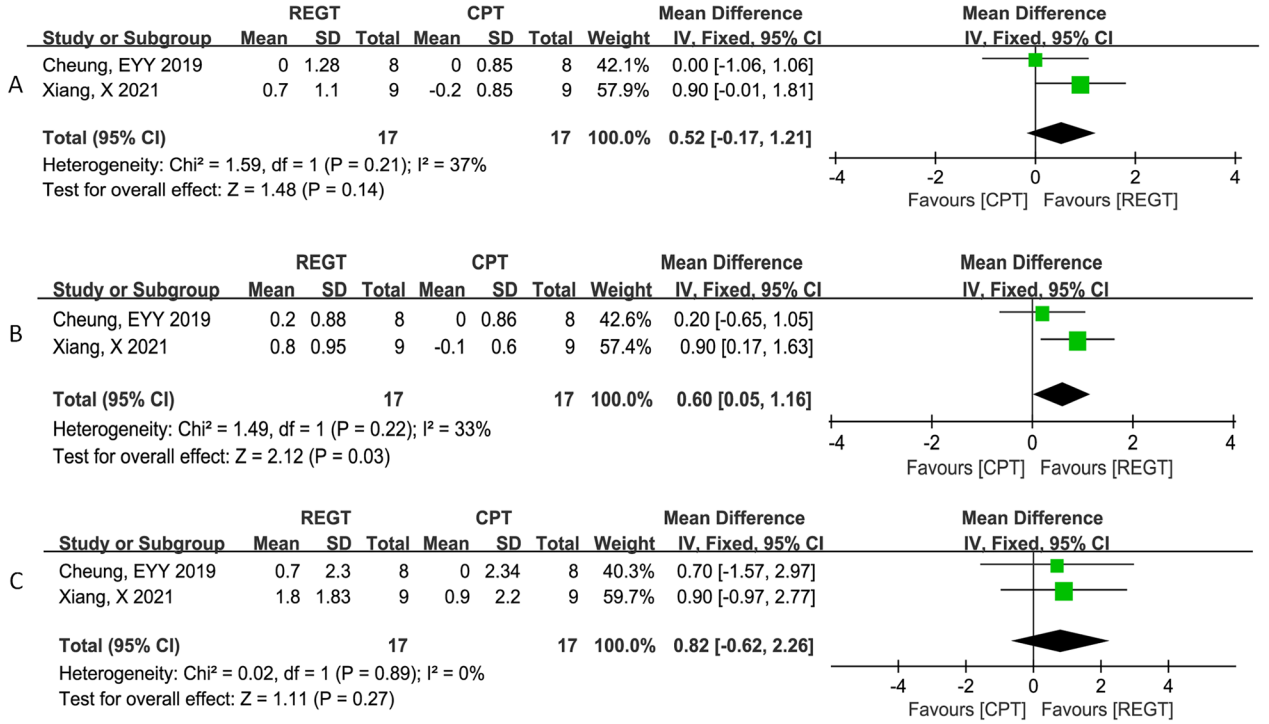

Fig. 7 Forest plots for REGT compared with CPT in respiratory function assessing the FVC (**A**), FEV1 (**B**) and PEF (**C**)

controlling their body posture [47]. By undergoing walking training under physiological conditions that can be repeated, patients are able to activate their trunk muscles more effectively, allowing them to adapt to postural control and maintenance while in motion. This, in turn, significantly improves their weight transfer and balance skills [48]. Similarly, our meta-analysis results indicate that patients undergoing robotic exoskeleton gait training exhibited significant improvements in the Timed Up and Go (TUG) test, the Walking Index for Spinal Cord Injury II (WISCI-II), and the Lower Extremity Motor Score (LEMS). Notably, the enhancement of trunk core stability emerged as a critical factor contributing to TUG improvements. The TUG indicator focuses on overall activity ability and dynamic balance. It reflects the comprehensive improvement of muscle strength and balance ability [49]. The use of robotic exoskeletons enables paralyzed spinal cord injury patients to walk and transfer independently, closely resembling their natural physiological state [50]. By utilizing exoskeleton robots as assistive devices, patients with spinal cord injuries can walk safely and independently, while experiencing the positive effects of rehabilitation training.

In this study, the comparison of walking function score results in patients after spinal cord injury was conducted. The meta-analysis included two important indicators: WISCI-II (Walking Index for Spinal Cord Injury) and LEMS (Low Extremity Motor Score). The internationally accepted indicator for evaluating lower limb motor function is the Lower Extremity Motor Score (LEMS), which is a standard for neurological classification of spinal cord injury developed by the American Spinal Injury Association (ASIA). LEMS is a critical evaluation metric utilized to ascertain the ASIA classification of spinal cord injury, with its effectiveness acknowledged both nationally and internationally [51]. WISCI II is frequently employed in rehabilitation facilities to assess the ambulation capabilities of SCI patients. Research has demonstrated that it exhibits consistent validity with the ASIA classification. The results of meta-analyses indicate that robotic exoskeleton gait training significantly enhances patients' WISCI-II and LEMS scores. This study aims to investigate the effects of repeated standing and walking exercises within REGT training on the strength and tension of lower limb muscles. Trainers aspire to preserve lower limb muscle strength to the fullest extent possible, even in the aftermath of nerve damage. It is common for patients with spinal cord injuries to experience prolonged periods of bed rest due to mobility challenges. Numerous studies have documented the detrimental effects of prolonged bed rest on the body, including decreased bone mass, muscle fiber atrophy, and muscle steatosis [52–55]. The use of lower limb robotic devices mitigates patients' bed rest duration, thereby indirectly alleviating the aforementioned adverse effects [52]. These enhancements consisted of a rise in the mass of the lower limb and appendages while observing a reduction in the total, lower limb, and appendicular adipose tissue [53, 54]. Moreover, the intervention also resulted in a substantial augmentation in the cross-sectional dimensions of the calf muscle and a growth of 14.5% in the bone mineral density of the tibia [55]. In addition, there was a decrease exceeding 5% in both subcutaneous adipose tissue and intramuscular adipose tissue [54, 55].

In our meta-analysis, we found that patients who underwent Lokomat robotic-assisted gait training therapy showed greater improvement in strength of lower limbs (LEMS) compared to patients who underwent CPT; however, patients who received robotic exoskeleton gait training rehabilitation did not show significant statistical differences compared to CPT. Both the WISCI-II and LEMS indicators significantly improved in the Lokomat group, while only the WISCI-II improved in the robotic exoskeleton group. This suggests that Lokomat therapy may be more effective in improving strength of lower limbs. However, it is important to note that our study did not directly compare Lokomat and exoskeleton for gait rehabilitation training in patients with spinal cord injury. Instead, we compared the Lokomat group to a conventional physical rehabilitation therapy (CPT) group, and the exoskeleton group to the CPT group. We found that the Lokomat group performed worse than the CPT group in terms of walking speed recovery, while the exoskeleton group performed similarly to the CPT group. These findings are consistent with a recent network meta-analysis that directly compared Lokomat and exoskeleton and found that exoskeletons may lead to better outcomes in walking speed [56]. However, it is important to consider the possibility of patient data publication bias, as Lokomat has been widely used clinically and has more available patient case data. Additionally, the high cost and technical limitations of robotic exoskeletons may limit their practical use in rehabilitation centers. Future studies should focus on conducting relevant clinical randomized controlled experiments to further analyze and compare the effectiveness of Lokomat and exoskeleton therapy in spinal cord injury rehabilitation.

Our study also found that REGT improves pulmonary function to some extent and may be more effective than traditional rehabilitation, particularly in terms of the indicator FEV1 (forced expiratory volume in one second). FEV1 is an evaluation index for assessing pulmonary reserve function. In patients with spinal cord injury, especially those with injuries above the thoracic 6 segment of spinal cord, the likelihood of pulmonary dysfunction increases. Although there are few studies on

cardiac function in the RCT literature we included, there is substantial evidence that REGT has a positive promoting effect on cardiac function in patients with spinal cord injury. Robert et al. [57] discovered that the upright heart rate of patients in the REGT group was significantly lower than that of the CPT group, and this effect was even more pronounced during long-term intervention training (24 weeks). Peter et al. [58] confirmed that REGT training has a similar effect to water exercise training in terms of increasing peak oxygen consumption (VO_2) and improving patients' pulmonary function and cardiovascular neuroadaptation. Orthostatic hypotension with tachycardia is a typical symptom in patients with spinal cord injury who are unable to promptly raise blood pressure due to associated autonomic dysfunction. REGT training provides external support, reduces the risk of falls for patients with spinal cord injuries, and makes them more psychologically and physically receptive to early standing and walking training. This maximizes the preservation and exercise of cardiopulmonary function and autonomic nervous system regulation. In addition, REGT induces a unique walking physiological rhythm. This change in posture activates intravascular baroreceptors, leading to a series of neural adjustments in the body [47, 59]. It may provide different stimulation to the sympathetic and parasympathetic nervous systems, thereby driving overall improvement in cardiopulmonary function [60, 61]. Furthermore, lower limb exoskeleton training can also offer various other health benefits, including improved bowel and bladder function, reduced muscle atrophy and spasm, and relief from neuropathic pain [62, 63]. These benefits contribute to a better quality of life and prognosis for patients.

Limitation

The studies included in the review had varying designs (2-, 3-, and 4-arm designs), durations, and types of robotic exoskeleton devices used. Additionally, the participants in each study had different characteristics. According to our quality assessment results of the RCTs, among the 15 included RCT articles, one-third of the RCTs (5 articles) had an average quality, while the remaining two-thirds had a good quality (Table 3). Although we obtained some results from the meta-analysis following data aggregation, the presence of various biases diminishes the certainty of the evidence presented in our final meta-analysis results (Table S4). The mode, intensity, and frequency of REGT varied across different rehabilitation centers. The duration of the rehabilitation training ranged from 4 to 8 weeks. The shortest training time per day reported was 30 min [64], while the longest training time was 90 min [65]. This variation in training duration may introduce some bias in the rehabilitation effect data.Furthermore, the degree and level of spinal cord injury among the patients included in each study are inconsistent. This means that the functional status of the lower limbs before the start of rehabilitation training varies greatly among patients. In three of the documents, the level of spinal cord injury reached ASIA level A [66–68], indicating complete paralysis of both lower limbs after surgery. This difference in patient data may result in some deviation in the data related to postoperative gait training and improvement in functional scores. Unfortunately, the included literature does not currently provide sufficient data to conduct subgroup analysis based on ASIA grading levels. It is recommended that future studies include more randomized controlled trials with larger sample sizes to address these issues more comprehensively and minimize any offset.

Conclusion

Robotic exoskeleton gait training is an effective method for improving walking balance and strength of lower limbs in patients with spinal cord injury compared to conventional physical gait training programs. REGT has shown significant improvements in walking balance, spinal cord recovery function scores, and to some extent, breathing and ventilation functions. However, there is no significant difference between the two programs in terms of lower limb walking speed and distance during the early post-injury period. After 6 months of injury, the conventional physical gait training becomes more advantageous in walking speed. However, further high-quality randomized controlled trials are needed to fully understand the effectiveness of robotic exoskeleton gait training on lower limb function, walking and cardio-pulmonary function for individuals with spinal cord injury.

Abbreviations

SCI	Spinal cord injury
REGT	Robotic exoskeleton gait training
CPT	Conventional physical training
10 MWT	10-M walk test
6 MWT	6-Min walk test
TUG	Time up to go
WISCI-II	Walking Index for Spinal Cord Injury II
LEMS	Lower Extremity Motor Scores
FEV1	Forced expiratory volume in one second

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12984-025-01649-1.

Additional file1 (DOCX 18 KB)

Additional file2 (DOCX 17 KB)

Additional file3 (DOCX 16 KB)

Author contributions
Liu SY, Chen FY and Yang LY contributed to methodology, design, and development of the study. Liu SY, Chen FY and Yin JQ share first authorship and equally contributed to data curation, acquisition, formal analysis and the writing of the manuscript. Yang LY and Wang GQ contributed to supervision, review and edit the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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