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Effectiveness of Robot-Assisted Gait Training on Gait and Gross Motor Function in Children with Cerebral Palsy: A Literature Review

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ABSTRACT

Background: Cerebral palsy (CP) causes motor impairments in children, including abnormal gait, muscle weakness, spasticity, and poor balance. Robot-assisted gait training (RAGT) provides intensive, repetitive gait practice using wearable exoskeletons or treadmill-based systems to promote neuroplasticity, but its effectiveness remains debated. **Objectives:** To review recent evidence on RAGT effectiveness in children with CP, comparing wearable and tethered systems and their effects on gait, balance, and gross motor function. **Methods:** A literature search was conducted in PubMed and Scopus (last 5 years). Experimental studies (including RCTs), observational studies, and reviews on RAGT in pediatric CP were selected and narratively synthesized. **Results:** Recent trials report that wearable RAGT improves Gross Motor Function Measure (GMFM) scores and balance compared to conventional therapy. In contrast, meta-analyses indicate that tethered treadmill-based RAGT does not significantly improve walking speed or distance over standard therapy. Wearable systems using assist-as-needed control allow adaptive overground gait training with more natural sensory feedback, whereas trajectory-controlled devices impose fixed gait patterns. **Conclusion:** Wearable RAGT with adaptive assistance appears effective in enhancing walking ability, balance, and gross motor function in children with CP, while tethered systems show limited additional benefit. RAGT should be applied as a complementary intervention with individualized protocols. Further research is needed to evaluate long-term outcomes.

Keyword: Assist-as-needed, Cerebral Palsy, Exoskeleton, Robot-Assisted Gait Training, Wearable Exoskeleton

ABSTRAK

Latar Belakang: Menelaah bukti terkini efektivitas RAGT pada anak CP, termasuk perbandingan sistem wearable vs tethered, dampaknya pada pola berjalan, keseimbangan, dan motorik kasar, serta mode kendali (*assist-as-needed vs trajectory-controlled*) dan intensitas latihan. **Tujuan:** Menelaah bukti terkini efektivitas RAGT pada anak CP, termasuk perbandingan sistem *wearable vs tethered*, dampaknya pada pola berjalan, keseimbangan, dan motorik kasar, serta mode kendali (*assist-as-needed vs trajectory-controlled*) dan intensitas latihan. **Metode:** Pencarian literatur dilakukan di PubMed dan Scopus (5 tahun terakhir) menggunakan kata kunci RAGT dan CP anak. Studi eksperimental, observasional, dan ulasan yang relevan dipilih dan disintesis secara naratif. **Hasil:** Studi terbaru menunjukkan RAGT *wearable* meningkatkan skor GMFM (berdiri/jalan/berlari) dan keseimbangan anak CP lebih signifikan dibanding terapi konvensional. Sebaliknya, meta-analisis RAGT *tethered* di *treadmill* menunjukkan tidak ada peningkatan signifikan pada kecepatan atau jarak berjalan dibanding kontrol. Eksoskeleton *wearable assist-as-needed* memberikan latihan berjalan adaptif dengan umpan balik sensorik fisiologis, sedangkan sistem *trajectory-controlled* memaksakan pola berjalan kaku. **Simpulan:** Bukti mendukung bahwa RAGT *wearable* efektif meningkatkan fungsi berjalan, keseimbangan, dan motorik kasar anak CP, dengan kontrol *assist-as-needed* sebagai faktor kunci. RAGT *tethered* belum terbukti lebih unggul dari terapi konvensional. Penggunaan RAGT direkomendasikan sebagai pelengkap terapi konvensional dengan protokol latihan

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terpersonalisasi. Penelitian lanjutan diperlukan untuk mengevaluasi efek jangka panjang dan optimasi desain eksoskeleton bagi anak CP.
Keyword: Anak Cerebral Palsy, Eksoskeleton, Intensitas Latihan, Latihan Berjalan, Rehabilitasi Robotik

1. Introduction

Cerebral palsy (CP) is the most common developmental motor disorder in children. Brain injury in individuals with CP disrupts the developing nervous system, resulting in abnormal motor experiences caused by altered neurological function, including weakness, spasticity, loss of motor control, and limited coordination. These abnormal sensorimotor experiences and movement restrictions have detrimental effects on the musculoskeletal system and cortical organization, creating a vicious circle.[1,2] A global systematic analysis found that the birth prevalence of CP (prenatal, perinatal, and postneonatal) is currently around 1.6 per 1,000 live births (95% CI: 1.5–1.7) in high-income countries. In contrast, data from low- and middle-income countries indicate that the prevalence can reach up to 3.4 per 1,000 live births (prenatal/perinatal data) in some regions.[3]

A vital issue in daily activities often involves gait and muscle control impairments.[11,4] Gait and balance problems, which are characteristic of CP, hinder children's functional abilities in everyday life, thereby necessitating intensive rehabilitation interventions. Robot-Assisted Gait Training (RAGT) is a modern rehabilitation method in which patients walk with robotic assistance, either through wearable exoskeletons or tethered treadmill-based systems. Robotic exoskeletons provide active torque support and sensory feedback to facilitate a more physiological gait pattern.[1,5]

RAGT provides high-intensity, repetitive gait training with a large number of repetitions, which can stimulate motor neuroplasticity in children.[5,6] However, scientific evidence regarding the effectiveness of RAGT, particularly the comparison between wearable (untethered) and tethered (treadmill-based) systems, remains mixed. Several early studies have reported improvements in gross motor function and mobility following RAGT, but meta-analyses of RCTs have shown less consistent results.[7–9] Therefore, this literature review aims to analyze recent studies on the effectiveness of RAGT in the pediatric CP population. The review focuses on comparing wearable and tethered RAGT systems, examining the impact of RAGT on gait function, balance, and gross motor skills, as well as evaluating device design and control modes (assist-as-needed versus trajectory-controlled) and training intensity. These findings will be discussed to assess the clinical relevance of RAGT in children with CP.

2. Methods

The literature search was conducted using indexed academic databases (PubMed/Medline, Scopus, Wiley, Elsevier), as well as SINTA-indexed journals and Google Scholar, covering publications from the past five years. The keywords used included "robot-assisted gait training," "cerebral palsy," "children," "exoskeleton," and "gait rehabilitation." Inclusion criteria consisted of experimental studies (including RCTs and case studies), observational studies, and systematic or narrative reviews related to RAGT in children with CP. This method followed previous systematic reviews by Cortés-Pérez et al. (2022) and Conner et al. (2022), who conducted searches in PubMed, Scopus, CINAHL, and other databases to identify RAGT studies in pediatric CP. The search yielded dozens of articles, which were then screened based on methodological relevance and population focus. Studies involving pediatric CP samples were prioritized. Data from the selected studies were synthesized descriptively according to the main RAGT topics (effectiveness, device design, control modes, and training intensity).

3. Discussion

3.1 Comparison of Wearable and Tethered RAGT

Recent literature indicates differences in outcomes between wearable RAGT (overground exoskeleton) and tethered RAGT (treadmill-based exoskeleton). In a large-scale clinical trial by Choi et al. (2024), 90 children with CP (GMFCS II–IV) underwent high-intensity RAGT using a wearable overground exoskeleton, compared with a conventional physical therapy control group. The results showed that the wearable RAGT group experienced significant improvements in total Gross Motor Function Measure (GMFM) scores, including the standing and walking/running/jumping dimensions, as well as in functional independence (PEDI-CAT), compared to the control group.[1] Pediatric Balance Scale scores and Gait Deviation Index (GDI) were also higher in the RAGT group at follow-up (4 weeks).[1]

These findings indicate that wearable exoskeletal RAGT, based on assist-as-needed torque control (where assistance is provided only when required), is effective in improving gait function and walking patterns in children with CP. In contrast, a meta-analysis by Conner et al. (2022) on RCTs of tethered RAGT (robotic gait systems such as gait trainers or Lokomat) reported that the use of tethered robots did not provide any significant additional benefits compared to standard therapy for mobility in children with CP. In that review, differences in the six-minute walk test, self-selected walking speed, and GMFM D/E scores between the tethered RAGT and control groups were not statistically significant.[88,10,11]

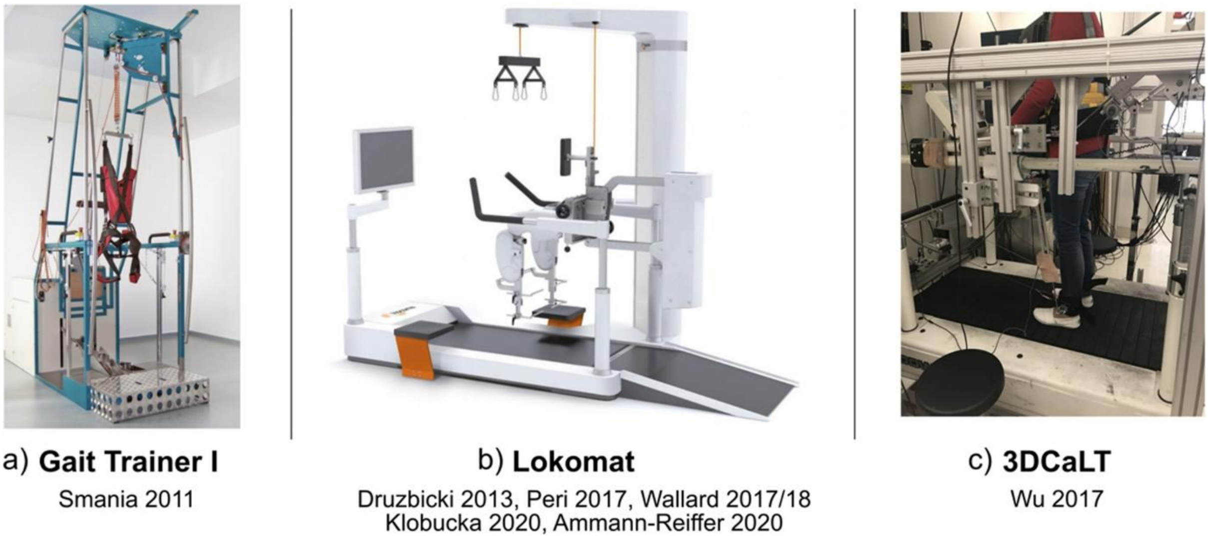

Figure 1. Robotic gait training devices utilized in each study, including (a) the Gait Trainer I, (b) the Lokomat, and (c) the 3DCaLT.[8]

In other words, at post-intervention evaluation, tethered RAGT tends to be comparable to conventional therapy. This difference in outcomes can be explained conceptually: wearable RAGT allows gait training in an overground environment that more closely resembles natural walking, with the body's own stabilization system and adaptive torque control that approximates a normal gait pattern.[1,8,12] This provides physiological sensorimotor feedback and enhances patient engagement in controlling their steps. In contrast, tethered RAGT typically involves treadmill-based training with pre-programmed, trajectory-controlled movement patterns and constant body-weight support. The tethered system tends to fix joint angles along a predetermined path, which in some cases may result in unnatural pelvic or body positioning if not properly adjusted to the child's anatomy.[8,13–15] Therefore, wearable exoskeletons are often considered more effective in improving dynamic balance and body alignment during walking compared to tethered systems.[16] In clinical practice, a hybrid approach (combining RAGT with conventional physical therapy) is also often recommended to maximize the transfer to daily functional activities.

3.2 Effects on Gait Function, Balance, and Gross Motor Skills

Recent studies have reported improvements in various aspects of motor function following RAGT interventions, particularly with wearable RAGT. Choi et al. (2024) found significant improvements in total GMFM scores and subscores (including standing and walking dimensions), as well as daily An increase in GMFM dimension E scores (walking, running, jumping) indicates improved gross motor function after robotic training. In addition, Pediatric Balance Scale (PBB) scores in the study increased more in the RAGT group, indicating enhanced balance control.[1]

A recent systematic review supports these findings, albeit with some qualifications. Cortés-Pérez et al. (2022) reported that RAGT generally improves walking speed and distance compared to conventional training. They found a positive standardized mean difference (SMD) for speed (SMD ≈ 0.56) and distance (SMD ≈ 2.0) after the intervention.[17] Walking, running, and jumping abilities were also better in the RAGT group (SMD ≈ 0.63).[17] However, differences in other parameters (such as gait quality or stability) were not always significant between RAGT and control groups. Similar results were reported by Hunt et al. (2022) in a systematic review of exoskeleton use, which concluded that exoskeleton training can reduce metabolic cost during walking and increase walking speed as well as hip and knee extension during the stance phase compared to pre-training levels.[18]

In addition, high-intensity training studies on wearable RAGT have shown positive effects on walking endurance. For example, Chmara et al. (2025) reported that 28 RAGT sessions using the EksoGT exoskeleton over 8 weeks significantly increased the 6-Minute Walk Test (6MWT) distance (from an average of 375 m to 418 m, $p < 0.01$) in children with CP classified as GMFCS I–III.[19] However, gait kinematic parameters (symmetry, joint angles, gait deviation index) did not show significant changes, indicating that independent gait patterns did not substantially improve despite the increase in endurance.[19] In other words, wearable RAGT can enhance walking strength and stamina without fully normalizing step patterns. This aligns with observations that exoskeletons improve functional abilities (mobility, speed, endurance) in children with CP, but progress in fine motor control or muscle pattern abnormalities (spasticity, coordination) still requires additional interventions.[18,19]

3.3 Device Design and Control Modes (Assist-As-Needed vs Trajectory-Controlled)

The design of RAGT influences how assistance is delivered. In general, there are two main control approaches: trajectory-controlled and assist-as-needed (AAN). In the trajectory-controlled mode, the robot (usually tethered to a treadmill) forces the user to follow a pre-programmed gait pattern. Joint positions are set along a fixed trajectory, with little or no adaptation to the patient's effort. In contrast, the AAN mode (more common in wearable exoskeletons) provides torque assistance only when needed, encouraging the patient to actively move part of the joints independently. An example of AAN implementation can be seen in the CPWalker platform: the robot offers several control modes, ranging from position control (following preset gait patterns) to impedance control or zero-force control, which require active participation from the child.[20] In the impedance mode, there are high, medium, and low levels of assistance, where deviations from the trajectory are designed to be more tolerable, motivating the user to exert as much effort as possible, at their own pace.[20] The zero-force mode allows the child to walk with joints fully moved independently, with minimal assistance from the exoskeleton. This mode is typically used when the child's motor control has improved but body stabilization is still needed.

Another important design feature is body-weight support (BWS) and treadmill speed. Most RAGT protocols adjust BWS and speed progressively: initially, a high level of body-weight support and a low speed are used to help patients learn movement patterns, which are then gradually reduced to increase patient participation. By modulating these parameters, RAGT can be tailored to match the child's progress. These modes allow for more flexible gait training; for example, studies on tethered Lokomat RAGT in CP also recommend using variable BWS and adaptive torque settings to make therapy more individualized. In summary, modern RAGT device design aims to balance between providing trajectory guidance and responsive assistance that encourages active movement in children (assist as needed).[1,20]

3.4 Training Intensity

RAGT training intensity has been identified as a key factor for rehabilitation success. Choi et al. (2024) compared three RAGT intensity protocols (high, comfortable, and low) in 30 children with CP classified as GMFCS II–III. The high-intensity group (high speed, low BWS) showed a significant improvement in GMFM standing dimension scores ($\Delta D \approx +8.3\%$) compared to baseline, while the comfortable-intensity group (moderate speed) also demonstrated GMFM improvement but to a lesser extent.[21] The comfortable group exhibited increased walking speed (not significant between groups), whereas the low-intensity group (high BWS, slow speed) showed improvements in the stability index.[21] All groups demonstrated improvements in daily adaptive function (Pedi-FIM), with the greatest increase observed in the comfortable-intensity group. These findings indicate that different intensities stimulate different outcomes: high-intensity training enhances motor strength, moderate-intensity training improves walking speed, and low-intensity training enhances balance control.[21] The key takeaway is the need to tailor RAGT intensity according to each child's specific rehabilitation goals. There is no single superior protocol for all; instead, the program should be individualized (e.g., high intensity to improve gross motor function, low intensity for children with balance impairments).[21]

3.5 Clinical Implications

These findings have important implications for the rehabilitation of children with CP. Recent RCT results support the integration of wearable RAGT as an adjunct to conventional physiotherapy: overground exoskeleton therapy can complement standard therapy by providing optimal assistance to the child's gait pattern.[1,19] The significant improvements in GMFM scores and walking ability indicate that RAGT functions effectively as an intensive and repetitive training stimulus. However, considering that tethered RAGT does not always significantly outperform conventional therapy.[8,22,23} The use of RAGT should be considered as part of a comprehensive therapy program rather than a replacement. In addition, protocol settings (duration, frequency, speed, BWS, control mode) need to be adjusted according to each child's characteristics. For example, children who need to improve walking speed may benefit from higher speed settings, while those with balance issues may benefit from stationary strengthening exercises and full-assist control modes at the beginning. Studies such as Moll et al. (2022), which used RAGT (HAL exoskeleton) during inpatient rehabilitation, showed mixed clinical results: there was a clinical improvement in GMFM scores, but the difference in walking speed between the RAGT group and the control group receiving other intensive therapies was not significant.[22] This indicates that in the context of comprehensive intensive therapy, the additional effect of RAGT may be minimal if conventional training is already sufficiently intensive. Therefore, it is important for practitioners to set realistic therapy goals and use RAGT in appropriate scenarios—for example, children who are less motivated or have severe motor deficits may benefit more from additional robotic stimulation.[5,22]

Child safety and comfort must also be taken into consideration; most studies report that RAGT is generally safe and well tolerated by children, with minimal side effects. However, the long-term effects of RAGT on motor development and quality of life in children with CP still require further investigation. Overall, current evidence supports that wearable RAGT, particularly with adaptive control, can improve gait function and balance in children with CP.[5,8] Tethered RAGT can still be considered for specific cases (such as children who require more controlled posture), but practitioners should be aware that its additional impact on mobility may be limited compared to conventional approaches.[8,24–26]

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3.7 *A Comparative Review of Recent Studies on Robot-Assisted Gait Training (RAGT) in Children with Cerebral Palsy*

Significant Findings

Several studies on robot-assisted gait training (RAGT) in children with cerebral palsy (CP) have reported clinically meaningful improvements in gait function and gross motor performance. For example, Choi et al. (2024) demonstrated significant increases in total GMFM scores—including standing and walking dimensions—as well as balance outcomes following wearable RAGT compared with conventional therapy.[21] Julien et al. (2024) reported significant improvements in gait speed and 6MWT distance in children receiving treadmill-based RAGT.[27] Similarly, Jin et al. (2020) observed improvements in GMFM Dimensions D and E, along with enhanced functional independence measured by WeeFIM and COPM following RAGT compared with standard care.[28]

Overall, RAGT provides clinical benefits for children with CP, including improved walking efficiency, as reflected by reduced completion times in functional gait tests such as the 10mWT and TUG,[29] and enhanced muscle activation patterns, as demonstrated in studies using wearable exoskeleton systems such as HAL.[30] However, several meta-analyses indicate that the advantages of tethered (treadmill-based) RAGT do not consistently exceed those of conventional therapy.

Table 1. Recent Studies on Robot-Assisted Gait Training in Children with Cerebral Palsy (2020–2025)

Author	Year	Method	Sample Size	Main Findings
Choi JY et al.	2024	Randomized Controlled Trial (compared with conventional therapy)	90 children with CP (GMFCS II–IV)	Wearable RAGT (overground exoskeleton) significantly improved total GMFM scores (particularly standing and walking/running dimensions), Pediatric Balance Scale scores, and Gait Deviation Index (GDI) compared with the control group.[21]
Julien L et al.	2024	Randomized Controlled Trial (G-EO treadmill vs conventional therapy)	40 children with unilateral CP (aged 4–18 years)	Gait speed and distance in the 6-Minute Walk Test (6MWT) increased more significantly following treadmill-based RAGT compared with controls. Improvements in sensorimotor brain connectivity were also observed after RAGT.[27]
Jin LH et al.	2020	Randomized crossover trial (Walkbot treadmill)	20 children with CP (GMFCS II–IV)	Significant improvements were found in GMFM Dimension D (standing) and Dimension E (walking/running), as well as functional scores (WeeFIM mobility and COPM) after RAGT compared with standard care. Energy expenditure during walking was reduced.[28]
Błażkiewicz M et al.	2024	Observational study (Lokomat as adjunct therapy)	26 children with CP (aged 4–23 years)	Completion time for the 10-Meter Walk Test (10mWT) and Timed Up and Go (TUG) decreased significantly after Lokomat RAGT. Step counts during training increased, with progressive improvements in walking distance and reductions in body-weight support (BWS) across sessions, indicating gait improvement.[29]
Takahashi K et al.	2025	Case report (HAL-2S wearable exoskeleton)	3 children with CP (GMFCS II and IV)	After 11–12 sessions of wearable RAGT using the HAL exoskeleton, all cases demonstrated increased hip and knee extension angles and enhanced agonist muscle activity during the stance phase. Mean hip extension angles increased, contributing to improved forward propulsion.[30]

Comparison Between Wearable and Tethered RAGT

Current evidence indicates notable differences in outcomes between wearable RAGT (untethered exoskeletons) and tethered RAGT (treadmill-based systems). Wearable RAGT tends to produce more pronounced improvements in gait function. Choi et al. (2024), using an overground wearable exoskeleton, reported significant improvements in GMFM scores and gait parameters compared with standard therapy.[21] In contrast, literature reviews suggest that treadmill-based RAGT has not consistently demonstrated additional significant benefits in walking speed or distance compared with conventional physiotherapy.

These differences may be explained by device control characteristics. Wearable RAGT systems commonly employ adaptive *assist-as-needed* control strategies that allow gait patterns to more closely resemble natural walking. Conversely, tethered systems typically operate along fixed trajectories with constant body-weight support. These distinctions influence sensorimotor feedback and muscle activation during training, making wearable RAGT more effective for enhancing dynamic balance and postural alignment during ambulation.[21]

Differences in Study Methods and Approaches

Over the past five years, RAGT research has employed diverse study designs. Randomized controlled trials (e.g., Choi 2024; Julien 2024; Jin 2020) used parallel or crossover designs to compare RAGT with standard therapy, with sample sizes ranging from 20 to 90 participants.[21,27,28] Observational studies (e.g., Błażkiewicz 2024) implemented RAGT as an adjunct to routine physiotherapy and evaluated pre- and post-intervention outcomes.[29] Case reports (e.g., Takahashi 2025) focused on detailed biomechanical changes in small patient cohorts.[30]

Additional methodological differences include device type and control mode. Treadmill-based systems such as Walkbot and G-EO typically utilize fixed trajectory control, whereas wearable systems such as HAL employ adaptive *assist-as-needed* control.[27,28] Outcome measures also varied widely, including GMFM scores, 6MWT, TUG, three-dimensional gait analysis, and electromyography (EMG).[28] Training intensity and duration differed across studies, most commonly involving 3–5 sessions per week over several weeks.

This methodological heterogeneity should be considered when interpreting results. Although many studies report positive trends following RAGT, variations in study design, patient characteristics (GMFCS level and age), and intervention protocols may influence individual study outcomes.

4. Conclusion

Recent literature indicates that wearable RAGT (untethered exoskeleton) is effective in improving walking function, balance, and gross motor skills in children with CP compared to conventional therapy alone. The use of torque-based assist-as-needed control appears to play an important role in the success of this therapy. In contrast, tethered RAGT (on a treadmill) has not demonstrated significant advantages over standard therapy in improving general mobility in children with CP. The intensity and configuration of RAGT training should be tailored to therapeutic goals; different intensity levels show varying effects on motor strength, walking speed, and balance control. For clinical application, RAGT is recommended as a complement, not a substitute, for conventional therapy, with appropriate protocol modulation. Future research should explore the long-term effects of RAGT on quality of life, social participation, and the optimization of exoskeleton design and control for the CP population. With a growing evidence base, RAGT holds great potential in pediatric CP rehabilitation —provided it is carefully integrated into comprehensive therapy programs.

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