Proceedings of CONF-SPML 2026 Symposium: The 2nd Neural Computing and Applications Workshop 2025
DOI: 10.54254/2755-2721/2026.TJ30022

The Effect of Wearable Devices on Gait Training in Children and Adolescents with Cerebral Palsy: A Scoping Review

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Abstract. Wearable technology serves as a promising inter- vention technique in pediatric rehabilitation, complementing traditional rehabilitation paradigms. However, this field lacks a systematic review of its application in rehabilitation intervention. This scoping review examines implementation results from 23 studies that utilize wearable devices for gait training in children with cerebral palsy (CP). We used the PRISMA framework to guide our systematic search through five major databases – PubMed, IEEE Xplore, ACM Digital Library, Embase, and Web of Science. Our search includes publications from January 2015 to July 2025. After the systematic review, we summarized three primary applications from the analysis: Real-time biofeedback, robot-assisted training, and adaptive algorithms. Our results demonstrated that Wearable sensors and devices demonstrate efficacy in most contexts with positive improvements in terms of measured gait-related parameters. Despite general positive inter- vention outcomes, substantial gaps persist in clinical implementa- tion protocols. Consensus on standardized experiment design and outcome metrics remains non-standardized. We advocate that the research community should focus on the standardization of experiment design and reporting frameworks for a more solid and replicable understanding of the role of wearable devices and sensors' rehabilitation intervention outcomes.

Keywords: gait training, balance, adolescent, child, cerebral palsy, wearable devices, rehabilitation

1. Introduction

Cerebral palsy (CP) is a brain disorder that appears in infancy or early childhood and permanently affects body movement and muscle coordination. Patients with CP demon- strate a large range of mobility impairments [1]. While people with mild CP do not need external assistance, people with severe CP cannot even sit or stand independently and may need a powered wheelchair. Traditional CP rehabilitation ap- proaches include periodic clinical assessments and therapist observations during organized sessions [2]. Two fundamental limitations emerge from this design. First, clinicians

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DOI: 10.54254/2755-2721/2026.TJ30022

only have access to discrete functional ability information rather than continuous performance data. Second, patients' clinical per- formance frequently diverges from real-world function because children exhibit different movement patterns under observation compared to naturalistic conditions when they are aware of being observed.

Wearable technology has progressed rapidly in recent years: Apple Watch Series has detection and ECG recording func- tions approved by the FDA [3], and Ekso Bionics develops wearable robotics to help treat people after a stroke, acquired brain injury, and multiple sclerosis [4]. These technologies enable continuous monitoring in natural environments, which also makes remote diagnosis possible. Previous systematic reviews focused on wearables for gait analysis in CP popula- tions, but these investigations do not cover practical training applications, especially in the children and adolescent subpop- ulation in which CP develops [5,6]. The relationship between technological capabilities and therapeutic implementation re- mains to be researched.

1.1. Objectives

Our primary objective is to determine whether wearable devices demonstrate improvements in gait function in children with CP and compare the results with traditional rehabili- tation methods. Our second objective is to examine current researchers' experiment design. For instance, whether there are common evaluation tasks and measurement parameters. Additionally, we investigate the sustainability of therapeutic gains if follow-up results are available in our reviewed papers. These questions demand rigorous investigation.

2. Methods

2.1. Information sources

The group conducted a literature search of PubMed, ACM Digital Library, IEEE Xplore, Embase,and Web of Science for all works published from January 2015 through July 2025. The primitive keywords are first defined and later improved by screening search results with the help of a PhD student. The search results from five databases are then imported into Zotero, a literature management tool for further analysis.

2.2. Search strategy

The keywords are defined to extract papers that address gait training or balance, include participants with cerebral palsy, mention any wearable device or sensor, and involve adolescents and children as participants.

Final keywords are organized into 4 parts. Keywords within the same part are connected with OR, and each part is connected to other parts with AND:

• wearable technology terms including 'wearable device', 'biological feedback', 'biofeedback', 'biosensor', 'inertial measurement unit', and 'accelerometer'

• balance and gait-related terms such as 'body equilibrium', 'gait', 'walking', 'postural balance', 'dynamic balance', 'gait training', and 'locomotor training'

• Minor population (≤ 18 years old) descriptors including 'adolescent', 'child', 'pediatric', and 'youth'

• movement coordination terms comprising 'movement dis- order', 'developmental coordination disorder', 'movement coordination', 'motor coordination', 'coordination diffi- culties', and 'DCD'

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2.3. Eligibility criteria

The group only includes peer-reviewed papers published in conferences and journals published later than December 31, 2014, and written in English and Chinese. Besides these pri- mary filters, manual selection by group members makes sure that selected papers discuss all of the following components:

1) Any form of wearable device or sensor that intervenes in the rehabilitation process. It should detect any form of postural balance or gait parameters (e.g., center of pressure, sway velocity, step length, cadence, etc.)

2) Patients with cerebral palsy. Participants with develop- mental coordination disorder, autism spectrum disorders, or other diseases are not considered in our review. (need unique attention)

3) Reports at least one evaluation metric (e.g., walking speed, postural sway, stride length, etc.) that quantizes the effect of one or more wearable devices or sensors on rehabilitation results.

2.4. Article screening

The systematic review process began with 194 articles identified through database searching. After removing 38 du- plicates, 154 unique articles remained for title and abstract screening. During this initial screening, 104 irrelevant papers were excluded based on predefined criteria. The remaining 50 articles underwent full-text assessment for eligibility. In this phase, 27 articles were excluded: 13 for being reviews or presentations, 5 for unavailable full texts, and 9 for lacking quantitative metrics. This screening process resulted in a final selection of 23 articles that met all inclusion criteria for the systematic review. Figure 1 illustrates the complete article screening and selection process.

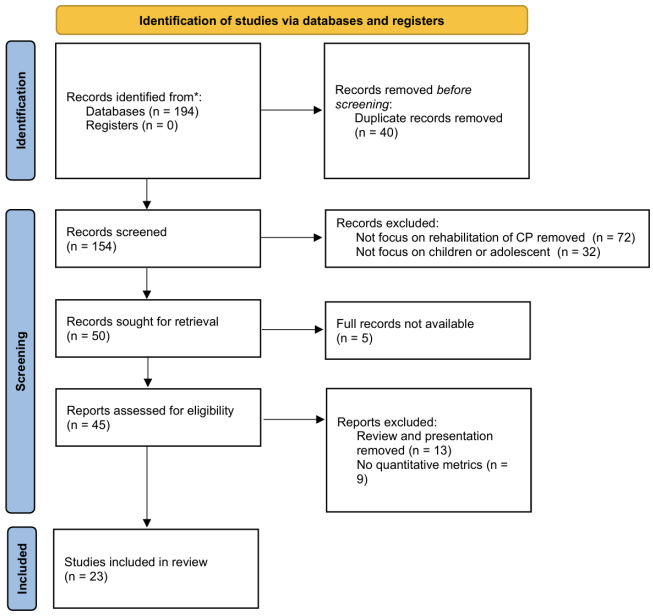

Figure 1. PRISMA flow diagram showing the article screening and selection process

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3. Results

3.1. Study characteristics

After rigorous examination, our systematic review included 23 studies between 2017 and 2025 [6-28]. We observed an increase in publication frequency in recent years, with six studies (26%) published in 2024 alone [14,16,20,23,25,26]. The increasing publication frequency reflects growing interest in wearable technology applications in CP rehabilitation of un- derage patients. The exact time distribution of the 23 included papers is: 2 studies in 2017 [7,24], 3 in 2018 [8,12,22], 3 in 2019 [9,15,18], 2 in 2020 [10,28], 1 in 2021 [21], 3 in 2022 [6,11,19], 2 in 2023 [13,17], 6 in 2024, and 1 in 2025 [27].

Within 23 studies, we found diverse research approaches. Most researchers went with either pre-post intervention de- signs or randomized controlled trials, but the number of participants varied dramatically. Choi et al. [20] reported a group of 90 children in their 2024 study, which is the largest group in our literature research. Other researchers recruited much smaller groups, ranging from just 5 to 10 children. This type of research mainly tested whether researchers' concepts work in practice. The typical study lasted for about 6 weeks. Although some researchers only needed a single session to test their concepts, others designed full 12-week training programs. Abbreviations: CP: Cerebral Palsy; GMFCS: Gross Mo- tor Function Classification System; EMG: Electromyography; AR: Augmented Reality; VR: Virtual Reality; IMU: Inertial Measurement Unit; RAGT: Robot-Assisted Gait Training; HAL: Hybrid Assistive Limb; AFO: Ankle-Foot Orthosis; ROM: Range of Motion; GMFM: Gross Motor Function Measure; GDI: Gait Deviation Index; CoP: Center of Pressure; TUG: Timed Up and Go; tVAF: Total Variance Accounted For; USCP: Unilateral Spastic CP; BSCP: Bilateral Spastic CP; PBS: Pediatric Balance Scale; CI: Confidence Interval.

3.2. Technology categories and applications

1) Electromyography (EMG) Biofeedback Systems: Eight studies (35%) used EMG-based biofeedback as their primary intervention strategy. Their wearable device systems provided real-time muscle activation feedback by visual displays, au- dio, and vibrotactile stimulation. Bertucco et al. [13] used vibrotactile EMG biofeedback and achieved range of motion improvements in 6 of 9 participants by approximately 5 degrees.

Flux et al. [17] developed an EMG-based gaming platform. In this design, muscle activation patterns controlled game elements. This gamification approach reported a 6.8% decrease in excessive muscle activity during the early stance phase (p=0.025) with high participant engagement scores. Conner et al. [11] reported 43-58% increases in soleus muscle activation and 52% improvements in appropriate co-contraction patterns following EMG biofeedback training.

2) Robotic Exoskeletons and Assistive Devices: Eight stud- ies (35%) investigated powered exoskeletons or robotic assis- tive devices. Lerner et al. [7] reported dramatic biomechanical improvements using a knee exoskeleton: knee extensor mo- ments decreased by 36% in early stance (p¡0.001) and 76% in late stance (p¡0.001), while peak knee extension increased by 12 degrees (p=0.001). These improvements occurred along with reduced vastus lateralis activity (12-24% decrease) and increases in hamstring (38-62%) and gastrocnemius (27-46%) activation.

In 2024, Choi et al. [20] conducted the largest randomized controlled trial in our papers. In this study, 90 participants received 12 weeks of robot-assisted gait training (RAGT). This group reported GMFM score improvements of 2.64 points (95% CI: 0.50-4.78) and Gait Deviation Index improvements of 6.48 points (p¡0.01). In a different study, Matsuda and team tested the Hybrid

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Assistive Limb (HAL) exoskeleton on children with GMFCS levels II to IV [22]. They observed that these children walked faster, with an important difference (p=0.046), and their GMFM scores also improved greatly (p=0.012).

3) Inertial Measurement Units (IMU) and Pressure Sen- sors: Four studies (17%) investigated IMUs in combination with force platforms, pressure sensors, or AR for real-time gait monitoring. Contini et al. [15] installed Magneto-Inertial

Measurement Units (MIMUs) on multiple locations of the patients: the central sternum level, at the L3 level, and on the lateral malleoli of both distal tibiae. These sensors served to provide biomechanical parameters to clinicians to help them select a customized Ankle-Foot Orthosis configuration. In the Saxena et al. [24] study, researchers reported a 100% participant retention rate with force platform balance training and visual feedback. They also reported improving Pediatric Balance Scale scores.

Fang et al. [16] combined ankle exoskeletons with pressure sensor feedback in their incline walking experiment setting. Researchers reported 34% increases in ankle power gener- ation (p=0.013), 15% increase in total ankle moment (p ¡ 0.001), and 66% increase in total ankle power (p ¡ 0.001). They also reported that for participants with GMFCS level III, biofeedback-plus-assistance was the only condition that resulted in greater ankle plantar flexion. It reveals the potential of multi-sensor systems compared to simpler single-sensor systems.

3.3. Follow-up and retention

Only 1 study (4%) included follow-up assessments beyond immediate post-intervention testing. Choi et al [20] conducted a 4-week follow-up study, and researchers report consistent improvements in the robot-assisted group in terms of balance control (mean difference, 1.48; 95% CI, 0.03-2.94) and Gait Deviation Index (mean difference, 6.48; 95% CI, 2.77-10.19) compared with the control group.

4. Discussion

4.1. Principal findings

Wearable devices help improve how underage individuals with CP walk. Even though the ways researchers did the studies are different, all the evidence keeps showing that wearable devices work in several areas. Each study used a slightly different approach—different devices, different steps, different metrics they measured, and different procedures they used to analyze the data. The differences are considerable, but the overall trend of positive results stays the same.

4.2. Clinical implications

Real-time feedback totally changes how therapy works between the therapist and the underage. Traditional therapy relies on the therapist closely observing and providing ver- bal cues—such as “Lift your foot more,” “Keep your body straight,” or “Push harder when you step off.” But many children and adolescents with CP cannot even tell when they are moving wrong because their objective senses do not function as well. Wearable sensors address this problem, though — they show how the kids are interacting with things like pictures, sounds, or even a little vibration. The good thing is that there are many effective ways to help, so clinicians can pick what is best for each child. For example, if a kid is at GMFCS Level I or II and likes games, VR might help them. But if a kid is at GMFCS Level III or IV and is really weak, they might need an exoskeleton to support

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them. If a kid struggles to control specific movements, EMG biofeedback could work by providing targeted feedback asynchronously. The problem, though, is that not everyone can access these technologies. Currently, they pose financial burdens — good exoskeletons can cost more than what many families' yearly income. Plus, insurance coverage for them is all over the place—some plans cover it, some do not. Until the costs decrease or society supports better coverage, children who could get better with these tools will not be able to use them.

Table 1. Summary of wearable device interventions for gait training in children with cerebral palsy - part 1 (N = 12)

First Year Author, Participants N			Technology Intervention	Key Outcomes	
EMG Biofeedback Systems (n=8)					
Bertucco, 2023 [13]	CP, GMFCS I-III	9	EMG + vibrotactile	1-month biofeedback training	Ankle ROM: +5° in 6/9 participants
Flux, 2023 [17]	Spastic CP, GMFCS I-II	18	EMG-driven gaming	Gaming with muscle control	Earlystanceactivity:↓6.8% (p=0.025)
Conner,2022 [11]	CP, GMFCS I-III	8	EMG + pressure sensors	Treadmill with dual feedback	Soleus: ↑43-58%; Co-contraction: ↑52%
Booth, 2018 [8]	Spastic CP, GMFCS I-II	25	VR + EMG/Motion capture	VR treadmill with biofeedback	Ankle power: ↑36% (p¡0.001); Step length: ↑13%
Booth, 2019 [18]	CP, GMFCS I-II	23	EMG + Motion capture	Real-timegait biofeedback	Synergies: +1 (p=0.008); Improved gait patterns
Bulea, 2018 [12]	CP, GMFCS I-II	7	EMG + exokeleton	Knee extension	Mean variance ratio decreases from 0.31 to 0.24 and from 0.50 to 0.37 for semitendinosus and vastus lateralis
Spomer,2024 [14]	CP, GMFCS I-III	8	EMG + exoskeleton	Audiovisual biofeedback	Motor control (tVAF) improvements
Boulay,2024 [23]	USCP, GMFCS I-II	30	EMG feedback system	Ankle training protocol	Velocity:0.72→0.77m/s (p=0.025)
IMU and Sensor Systems (n = 4)					
Guinet, 2022 [6]	CP,GMFCS I-III	25	IMUs + AR display	AR-guided walking	Speed: ↑14% (p¡0.001);Time on target: 81% vs 55%
Contini,2019 [15]	CP,GMFCS I-II	10	IMU sensors + Ankle-Foot Orthosis	AFO gait training	Step length: +0.06m (p=0.047)
Saxena, 2017 [24]	BSCP, GMFCS II-III	14	Force platform	Balance training with feedback	PBS improved; 100% retention rate
Harshe, 2024 [26]	CP, GMFCS I-III	8	Multi-sensor system	Primed resistance + feedback	Ankle power: ↑25% (p=0.021)

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4.3. Limitations

Current sample sizes are small, which means that they are serving as pilot studies, and researchers cannot rely on those results for children. The average number of people per study is 17. Also, CP is not the same for everyone and contains subdivisions. What works for spastic diplegia kids might do nothing for those with athetoid CP. Worse, most studies only sign up GMFCS Level I or II kids—that is 71% of participants—but Level III or IV kids need this help way more. Then there is an issue with how researchers check if their design works — there is no golden standard. Everyone tracks different metrics and does it in their own task scenario. Thus, it is difficult to compare a study that uses 3D technology to follow movement with one that just uses a stopwatch. A follow-up study is merely considered too. CP stays with a kid for life, but current research only checks for 6 weeks. There are no studies that follow kids for 6 months, a year, or 5 years. This can be attributed to the lack of funding and participants dropping out before the study finishes. And there can be bias in publications published. Studies where the treatment flopped hardly get published. Negative results exist, but only positive ones get published, talked about, and even tested again. The effects we screen in the papers may not be as complete and representative as the total experiments conducted so far.

Table 2. Summary of wearable device interventions for gait training in children with cerebral palsy-part2(N=11)

First Author, Year	ParticipantsN	Technology	Intervention	KeyOutcomes
RoboticExoskeletons (n=8)				
Lerner, 2017 [7]	CP, GMFCS I-II	7	Kneeexoskeleton	Powered knee assistance	Kneemoment: ↓76%; Extension: +12°(p=0.001)
Choi,2024 [20]	CP, GMFCS II-IV	90	Wearablerobot	12-week RAGT program	GMFM: +2.64 (CI: 0.50-4.78); GDI:+6.48
Kawasaki, 2020 [10]	CP, GMFCS I-III	10	Hipexoskeleton	Hip flexion assistance	Hipflexion:+13.4°(p=0.039
Conner, 2020 [28]	CP, GMFCS I-II	6	Wearable adaptive resistance ankle exoskeleton	10 sessions over 4 weeks (20 min/session)	↑17% plantar flexor strength (p=0.02), ↑39% walking speed (p=0.04), ↓33%metaboliccost of transport (p=0.03), ↑13%6MWT distance(p=0.04)
Conner, 2021 [21]	CP, GMFCS I-II	5	Exoskeleton+EMG	Multi-musclecoordination	Co-contraction:↓29%(p=0.02)
Conner, 2022 [19]	CP, GMFCS I-III	8	Poweredankledevice	Progressive resistance	significant increase for the combinedankleexoskeletonresistance andplantarpressurebiofeedbackin meanandpeaksoleusactivity
Fang,2024 [16]	CP, GMFCS I-III	12	Ankleexo+sensors	Incline walking withfeedback	Anklepower:↑34%(p=0.013)

DOI: 10.54254/2755-2721/2026.TJ30022

Table 2. (continued)

Matsuda, 2018 [22]	CP, GMFCS II-IV	6	HALexoskeleton	HAL-assisted walking	Speed: ↑ (p=0.046); GMFM: ↑ (p=0.012)
OtherTechnologies (n=3)					
Booth, 2019 [9]	CP, GMFCS I-II	23	Motion capture system	Gaitadaptation training	Step length symmetry improved
Alhashimi, 2024 [25]	Hemiplegic CP	25	Gamingbalance board	Weight shifting exercises	CoP excursion: ↓ (p¡0.05); TUG improved
Lohss, 2025 [27]	CP, GMFCS I-II	22	VR + Motion motion capture	natural walking in a virtual environment	Lateral stability: +6.4mm (p¡0.05)

4.4. Future directions

Researchers need to reach a consensus on a set of standard- ized core outcome measures. Every study ideally should use the same guidelines to design task scenarios and statistical metrics calculation. The aim to generate comparable data across studies. The Gross Motor Function Measure (GMFM) system can be a starting point [29]. It is an observational clinical tool designed to evaluate change in gross motor function in children with cerebral palsy that contains a four- point scale consisting of 66 or 88 items divided into five dimensions of gross motor function.

Researchers need to focus on broader studies that span a longer period. They need to have more people participating, and the follow-up should be conducted and not end too early.

Additionally, researchers also need to develop and test adaptive algorithms that can adjust training based on an individual kid's condition. Every kid reacts differently, and there are studies that show the supremacy of adaptive and customized training. An intelligent system could tweak the training difficulty, change the way feedback is given, or switch up the reward method, all based on how that specific kid is progressing.

Optimizing the cost-effectiveness also helps when promot- ing the usage of wearable devices. And another direction is to design systems that support remote training to create home- based rehabilitation programs can make this kind of help accessible to more people. No study in our screened papers has attempted in field tasks. As in lab test scenarios may cause psychological burden to participants, in field task data may have a different distribution, and clinicians adapt in lab practices with more challenges in field settings.

5. Conclusion

From these 23 papers, we confirm that wearable devices can improve gait rehabilitation of children and adolescents with CP. Related technologies demonstrate efficiency in various systems: exoskeleton systems make previously impossible, practical volumes in conventional therapies possible by provid- ing assistance or resistance; biofeedback systems provide more information than verbal responses from clinicians; and VRs transform therapy sessions into serious gaming experiences.

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However, challenges persist for further exploration of the potential of wearable devices. Researchers need to standard- ize experiment designs to perform meaningful comparisons between trials from different groups. Also, the limited sample size and missing statistical metrics, such as confidence inter- vals or p-values, raise questions about the generalizability of current results. Finally, follow-up periods, which are rarely conducted in current research, should be considered more for long-term intervention effect evaluations.

Future work will require engineers, clinicians, researchers, and patient families to collaborate on turning experimental systems into clinical practices. Although questions remain, the current 23 papers and some filtered studies show that the field is working towards the correct direction that incorporates more complex systems in terms of hardware and software for a more real-time and personalized rehabilitation experience. Children with CP should have access to all beneficial interventions, and wearable device interventions can be one hope for them.

Acknowledgement

Detao Ma, Zhixian Sheng, and Shugao Zhang contributed equally to this work and should be considered co-first authors.

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