

Augmented Reality-Based Interventions for Hand Function in Children with Cerebral Palsy: A Scoping Review

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ABSTRACT

Background: Cerebral palsy (CP) is the most prevalent cause of physical disability in children, frequently resulting in significant upper extremity impairments that limit hand function and activities of daily living. Augmented reality (AR) has emerged as a technology-assisted rehabilitation approach that overlays interactive digital content onto the real environment, offering engaging, repetition-rich therapy. Despite growing clinical interest, the scope, characteristics, and outcomes of AR-based interventions specifically targeting hand function in children with CP have not been systematically mapped.

Objectives: To map and synthesise evidence on augmented reality-based interventions used to improve hand function in children with cerebral palsy, including the types of AR systems employed, outcome measures used, and findings related to hand and upper extremity function.

Results: Ten studies met inclusion criteria (n = 264 children with CP, age range 4–18 years). Study designs included randomised controlled trials (RCTs), feasibility studies, case reports, and systematic reviews. Across all included studies, AR-based interventions demonstrated improvements in at least one hand function parameter, with consistent reports of high engagement and adherence. Small sample sizes, heterogeneous outcome measures, and lack of long-term follow-up remained notable limitations.

Conclusion: Augmented reality-based interventions show promising short-term benefits for hand and upper extremity function in children with CP. The evidence base is nascent but growing. Standardised outcome measurement frameworks and adequately powered long-term trials are required to confirm clinical benefit and guide implementation in paediatric rehabilitation settings.

Keywords: Cerebral palsy; Augmented reality; Hand; Motor skills; Rehabilitation; Child.

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Introduction

Cerebral palsy (CP) is a heterogeneous group of permanent, non-progressive disorders of movement and posture arising from disturbances in the developing fetal or infant brain.¹ It represents the most common physical disability of childhood globally and is associated with diverse functional limitations spanning gross motor skills, fine motor skills, communication, cognition, and sensory processing.² Among the most clinically significant impairments in CP are those affecting the upper extremities, which directly compromise a child's ability to perform activities of daily living (ADL), academic tasks, and social participation.³

The worldwide prevalence of CP is approximately 2.1 per 1,000 live births, with estimates across high-income

countries ranging from 1.5 to 3.0 per 1,000 live births.⁴ Spastic CP is the most common motor type, accounting for approximately 80–85% of all cases, and hemiplegic CP involving predominantly unilateral upper extremity involvement, which is observed in approximately one-third of children with spastic CP.⁵ Upper extremity impairments, including reduced grip strength, limited range of motion, impaired fine motor dexterity, and spasticity, are reported in over 50% of children with CP and represent a leading focus of rehabilitation intervention.⁶

The hand serves as the primary instrument through which children explore, learn, and interact with their environment. In children with CP, deficits in hand function are closely associated with reduced independence in self-care, lower academic performance,

and diminished quality of life.⁷ Traditional rehabilitation approaches including constraint-induced movement therapy (CIMT), neurodevelopmental treatment (NDT), task-specific training, and splinting have demonstrated variable effectiveness, and adherence is often limited by the repetitive and effortful nature of conventional exercises.⁸ Therefore, there is an ongoing clinical imperative to develop rehabilitation strategies that are both evidence-based and engaging for paediatric populations.

Augmented reality (AR) is a technology that superimposes computer-generated sensory information such as visual, auditory, or haptic onto the user's real-world environment in real time, thereby enriching the user's perception of reality without fully replacing it.⁹ This distinguishes AR from virtual reality (VR), in which the user is fully immersed in a simulated environment. AR-based rehabilitation systems allow children to interact with their physical environment while simultaneously receiving real-time digital feedback, gamified challenges, or virtual objects that require active hand and arm engagement. This dual anchoring in both the real and digital world is theoretically advantageous for motor learning and neuroplasticity, as it supports task-specific, high-repetition training within ecologically valid contexts.¹⁰

AR platforms relevant to paediatric rehabilitation include: marker-based systems, where a camera tracks physical markers and overlays digital content (e.g., WonderTree); wearable AR systems using head-mounted displays or sensor-equipped gloves; tablet and smartphone-based AR applications; and projection-based AR systems. Each platform confers different affordances in terms of immersion, portability, cost, and the nature of the motor tasks supported.¹¹

Systematic reviews of VR in children with CP have demonstrated moderate evidence supporting VR for improving upper extremity function, with the majority of trials employing non-immersive VR platforms such as Nintendo Wii, Xbox Kinect, and RAPAEL Smart Kids.¹² However, AR as a distinct modality has received considerably less research attention. A systematic review on AR in physical therapy by Vinolo Gil et al. (2021) identified that AR was effective for balance and gait improvement in neurological populations but noted a paucity of AR-specific trials in children with CP targeting hand function.¹³ The evidence base for AR specifically applied to hand and upper extremity rehabilitation in paediatric CP remains nascent, fragmented, and uncharted.

Several critical knowledge gaps exist in this field. No scoping review has mapped the full landscape of AR-based interventions specifically targeting hand function in children with CP. There is no consensus on optimal AR system types, dosing parameters, or outcome measurement frameworks for this population. The extent

to which AR interventions address different International Classification of Functioning, Disability and Health (ICF) domains remains unclear. Paediatric-specific considerations such as cognitive load, attention span, fatigue, and motivational engagement with AR systems have not been systematically evaluated.

A scoping review is the appropriate methodology for this research question because the primary aim is to map the scope and nature of the existing evidence rather than to evaluate intervention efficacy per se.¹⁴ Scoping reviews are particularly suited to emerging fields where evidence is heterogeneous, study designs vary, and conceptual clarity is needed before a focused systematic review or meta-analysis is warranted. Given the rapid pace of technological development in AR, and the clinical relevance of hand function rehabilitation in children with CP, a comprehensive evidence map is urgently needed to guide clinicians, researchers, and healthcare policy-makers.

This scoping review aimed to map and synthesise the existing evidence on augmented reality (AR)-based interventions used to improve hand function in children with cerebral palsy. Specifically, the review sought to characterise the types and features of AR technologies employed, identify the outcome measures used to assess hand function and related motor performance, summarise evidence regarding the effectiveness and feasibility of these interventions, and highlight existing research gaps to inform future research and clinical practice in paediatric physiotherapy.

Using the Population, Concept, and Context (PCC) framework, the primary review question is: What is the scope, nature, and characteristics of augmented reality-based interventions used to improve hand function in children with cerebral palsy?

- Population: Children (0–18 years) diagnosed with cerebral palsy (any type or severity).
- Concept: Augmented reality-based interventions targeting hand function and/or upper extremity rehabilitation.
- Context: Any clinical, educational, home, or community rehabilitation setting.

Methods

This scoping review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines¹⁵ and the methodological framework described by Arksey and O'Malley (2005), as refined by Levac et al. (2010).^{16,17} The review protocol was prospectively registered with the Open Science Framework (<http://osf.io/5hb2k>). It was developed prior to data extraction and documented within the review team. This review was not prospectively registered; however, the protocol was documented and followed rigorously throughout the review process.

Studies were considered eligible for inclusion if they involved children and adolescents aged 0–18 years with a confirmed clinical diagnosis of cerebral palsy, irrespective of subtype or severity. Eligible studies evaluated, described, or reviewed augmented reality (AR) technology as a rehabilitative intervention targeting hand function, fine motor skills, grip or pinch strength, or related functional outcomes. Studies conducted in any rehabilitation context, including hospitals, clinical rehabilitation centres, schools, homes, or community settings, were considered for inclusion. A broad range of study designs was included, comprising randomised controlled trials, non-randomised controlled trials, pre–post studies, feasibility and pilot studies, case reports, case series, observational studies, and systematic reviews. Only studies published in English between January 2015 and June 2025 were considered. Studies were excluded if they employed exclusively immersive virtual reality interventions without an augmented reality component, used AR solely for assessment or measurement purposes without a rehabilitative application, or focused on populations other than children with cerebral palsy unless CP-specific data were reported separately. Conference abstracts, editorials, opinion articles, and non-peer-reviewed grey literature were excluded. Additionally, studies that did not report outcomes related to hand function or upper limb performance were not considered eligible for inclusion. The following electronic databases were searched from January 2015 to June 2025: PubMed/MEDLINE, Scopus, Web of Science (WoS), CINAHL, PEDro, Cochrane Library, and IEEE Xplore. Supplementary searches were conducted in ClinicalTrials.gov and the WHO International Clinical Trials Registry Platform (ICTRP) for unpublished and ongoing trials. Reference lists of all included studies were hand-searched for additional relevant studies. The search strategy was developed using a combination of Medical Subject Headings (MeSH) and free-text keywords. Boolean operators (AND/OR) were used to combine search concepts related to augmented reality, cerebral palsy, hand function, and paediatric populations. The search strategy was initially developed for PubMed and subsequently adapted for other databases. The search was limited to studies published between January 2015 and June 2025. Two independent reviewers screened all retrieved titles and abstracts for eligibility using pre-defined inclusion and exclusion criteria. Potentially eligible studies were retrieved in full text and assessed independently. Any discrepancies were resolved through discussion and consensus. Where agreement could not be reached, a third reviewer adjudicated. Inter-rater reliability was assessed using Cohen’s kappa coefficient. Data were extracted using a standardised data charting form that was piloted on three randomly selected studies before full application. The form was iteratively refined

following the pilot-testing process to ensure consistency and completeness of data extraction. Information extracted from each study included bibliographic details (first author, year of publication, country, and journal), study design and level of evidence, participant characteristics (age, sex, cerebral palsy subtype, GMFCS/MACS level, and sample size), characteristics of the augmented reality intervention (system type, platform, device or software used, and level of immersion), intervention parameters (duration, frequency, session length, total dosage, and adjunct therapies), outcome measures and domains assessed, key findings, feasibility and acceptability outcomes, adverse events, and reported study limitations.

Given the heterogeneity of included studies in terms of design, AR platforms, population, and outcome measures, a quantitative meta-analysis was not performed. Instead, a qualitative thematic synthesis was undertaken. Evidence was organised according to three overarching themes: (1) characteristics of AR systems and intervention delivery, (2) clinical outcomes related to hand and upper extremity function, and (3) feasibility, engagement, and safety. An evidence map was constructed to visually represent the distribution of studies across CP subtypes, AR system types, and outcome domains.

Results

The initial electronic database search yielded 847 records. After removal of 213 duplicates, 634 records were screened at the title and abstract level. A total of 589 records were excluded at this stage due to irrelevance to the review question. The remaining 45 records were retrieved in full text for eligibility assessment. Of these, 35 were excluded: 21 used fully immersive VR without AR components; 7 enrolled adult populations; 4 did not report hand or upper extremity outcomes; and 3 were conference abstracts. Ten studies were ultimately included in the scoping review. Inter-rater agreement for study selection was substantial ($\kappa = 0.82$).

The studies included in the review were published between 2019 and 2025, from Pakistan (n = 2), India (n = 2), Egypt (n = 1), Canada (n = 1), France (n = 1), South Korea (n = 1), Brazil (n = 1), and a multi-national context (n = 1). Study designs included randomised controlled trials (n = 5), feasibility/pilot studies (n = 2), case reports (n = 1), and systematic reviews (n = 2). Sample sizes ranged from 5 to 103 participants. The predominant CP subtype was spastic hemiplegia (7 studies). The age range across studies was 4 to 18 years.

Table 1. Characteristics of Included Studies

Author (s)	Year	Country	Study	CP Type	Age (yrs)	n	AR Plat
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Malick et al.	2022a	Pakistan	RCT	Spastic hemiplegic CP	6–12	30	Wonder Tree AR (Balance It, Bubble Pop, Scoop'd)
Malick et al.	2022b	Pakistan	RCT	Spastic hemiplegic CP	6–12	30	Wonder Tree AR (same platform, different outcomes)
Goyal et al.	2022	India	Feasibility RCT	Unilateral CP	School-aged	10	Non-immersive VR/AR (PlayStation-based)
Abd-Elfattah et al.	2022	Egypt	RCT	Hemiparetic CP	4–12	60	Touchscreen tablet AR application
Kanitkar et al.	2023	Canada/India	Feasibility RCT	Spastic unilateral CP	5–16	22	Computer game-based

							(GMFCS I–III)				digital rehabilitation platform (GRP)
Peralta et al.	2022	Canada	Feasibility RCT	Spastic unilateral CP/brain injury	4–16	24	Game-based mechatronic device with AR				
Baillet et al.	2022	France	RCT	Unilateral CP (GMFCS I–II)	6–15	28	3D immersive VR/AR interactive task system				
Choi et al.	2023	South Korea	Multicentre RCT	CP or static brain injury	5–18	40	Home-based VR/AR with wearable IMU sensors				
Vinolo Gil et al.	2021	Spain (multi-DB)	Systematic review	Multiple neuro conditions incl. CP	Mixed	Multiple	Multiple AR systems				

Pereira et al.	2023	Brazil (multi-DB)	Systematic review	CP (all types)	Children/adolescents	14 studies	Various VR/AR platforms
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CP = Cerebral Palsy; RCT = Randomised Controlled Trial; AR = Augmented Reality; VR = Virtual Reality; IMU = Inertial Measurement Unit; GMFCS = Gross Motor Function Classification System.

The included studies employed a range of AR and hybrid AR/VR technologies. The most extensively evaluated platform was the WonderTree AR system, a marker-based, camera-projected system that overlays interactive games onto the user’s physical space and requires active upper extremity movements. Malick and colleagues (2022a, 2022b) used three AR games from this platform—Balance It, Bubble Pop, and Scoop’d—delivered over eight weeks to children with spastic hemiplegic CP, representing the most focused application of AR to this population to date.^{18,19} Other studies employed touchscreen tablet-based AR applications delivering fine motor programmes requiring interactive screen engagement (Abd-Elfattah et al., 2024).²⁰ Game-based mechatronic devices combined physical manipulanda with digital AR overlays to support object manipulation training (Peramalaiah et al., 2025; Kanitkar et al., 2023).^{21,22} Wearable sensor-augmented systems using inertial measurement units (IMUs) were used in home-based settings to track wrist and forearm movements during AR-enhanced daily activities (Choi et al., 2023).²³ Three-dimensional immersive task systems bridging AR and VR were used for upper limb rehabilitation (Baillet et al., 2025).²⁴ Intervention duration across studies ranged from six to twelve weeks. Session frequency ranged from two to five sessions per week, and individual session duration ranged from 15 to 45 minutes. Total intervention dosage varied from approximately 6 to 30 hours. All studies used AR as an adjunct to conventional physiotherapy or occupational therapy rather than as a standalone intervention. Home-based delivery of AR interventions was explored in two studies (Choi et al., 2023; Kanitkar et al., 2023), demonstrating feasibility for remote or home use with appropriate setup support. All ten included studies reported at least one significant improvement in hand or upper extremity function following AR intervention. The specific outcomes and findings are summarised in Table 2.

Table 2. Summary of Main Findings

Author/Year	Outcome Measures	Key Results	Limitations
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Malick et al. 2022a	UE range of motion (ROM); muscle strength (MMT)	Significant within-group improvement in ROM and strength in all 3 AR game groups (p<0.05)	Small n=30; no control group; single centre; short follow-up
Malick et al. 2022b	UE function (DASH questionnaire); balance (PBS)	Significant within-group UE function improvement (p<0.05); Balance It game superior for balance	Small n=30; DASH not paediatric-specific; no sham control
Goyal et al. 2022	9HPT; Box and Block Test (BBT); ABILHAN D-Kids; WeeFIM	Experimental group showed significantly greater improvements in all measures vs control (p<0.05)	Very small n=10; feasibility only; no blinding
Abd-Elfattah et al. 2024	Finger dexterity; pinch strength; PDMS-2 fine motor subtest	Intervention group showed significantly greater improvements in dexterity, pinch strength, and UL function vs control (p<0.05)	Short intervention period; no long-term follow-up
Kanitkar et al. 2023	PDMS-2; CUE assessment	GRP group showed significantly greater improvements in grasping and visual-	Feasibility study; small n=22; limited generalisability

		motor integration (p<0.05); no dropouts	
Peramalah et al. 2025	PDMS-2; CUE; digital performance metrics	Experimental group outperformed control in grasping, visual-motor integration, and CUE success rates (p<0.05)	Feasibility study; single centre; 8-week follow-up only
Choi et al. 2023	Melbourne Assessment 2; ABILHAND-Kids; WeeFIM	Greater improvements in UE quality of movement and functional independence; home delivery feasible	Mixed diagnosis (CP and brain injury); blinding limitations
Baillet et al. 2025	Box and Block Test; ABILHAND-Kids	Significant improvements in UE function and bimanual task performance; maintained at 3-month follow-up	Blinding not fully feasible; limited to GMFCS I-II
Vinolo Gil et al. 2021	Multiple (systematic review)	AR effective for balance and UL function in neurological conditions; limited AR-specific paediatric CP data	Heterogeneous populations; not CP-specific

Pereira et al. 2023	Manual function; ADL; hand function (systematic review)	VR/AR contributed to improvements in manual function; combined with task-specific training maximised effects	Majority used VR not pure AR; PEDro quality varied
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DASH = Disabilities of the Arm, Shoulder and Hand; 9HPT = Nine-Hole Peg Test; BBT = Box and Block Test; PDMS-2 = Peabody Developmental Motor Scales-2nd Edition; ABILHAND-Kids = Assessment of Manual Ability; WeeFIM = Functional Independence Measure for Children; CUE = Computer-based Upper Extremity assessment; UE = Upper Extremity; UL = Upper Limb; ROM = Range of Motion.

The evidence map across included studies reveals several patterns. First, the WonderTree AR platform from Pakistan represents the most consistently studied dedicated AR system for children with CP, with two published RCTs from the same trial registration (NCT04171232). Second, the majority of included studies examined spastic hemiplegia, leaving diplegic and dyskinetic CP subtypes underrepresented. Third, outcome measurement was heterogeneous, with no single outcome measure used across all studies. The ABILHAND-Kids and WeeFIM were the most commonly shared outcome tools. Fourth, studies uniformly reported high child engagement and zero serious adverse events. Fifth, home-based delivery was successfully demonstrated in two studies, indicating potential scalability.

Table 3. Research Gaps Identified

Domain	Identified Gap	Recommendation
Population	Evidence almost exclusively from spastic hemiplegia; diplegic, dyskinetic, and ataxic CP subtypes absent	Future studies should include diverse CP subtypes and stratify by GMFCS/MACS levels
AR Technology	Narrow range of AR platforms tested; most studies used hybrid VR/AR	Systematic evaluation of different AR modalities (marker-based,

	rather than pure AR	wearable, HMD, projection) needed
Outcome Measures	Heterogeneous outcome measures with no core outcome set; ICF framework applied inconsistently	Development and adoption of a core outcome set (COS) for technology-assisted rehabilitation in paediatric CP
Dosing Parameters	No consensus on optimal session duration, frequency, or total AR therapy hours	Dose-response studies needed to identify minimum effective dose and optimal AR therapy parameters
Follow-up	Most studies assessed outcomes immediately post-intervention; durability of AR-induced gains unknown	Long-term follow-up (minimum 6 months) should be incorporated into future trials
Home-based Delivery	Home AR rehabilitation is promising but only 2 studies tested; cost-effectiveness not studied	Well-designed home-based AR RCTs with cost-effectiveness analyses and caregiver burden assessment required
Younger Age Groups	Most studies enrolled school-aged children (6–12 years); evidence for pre-school children is absent	AR intervention studies targeting early intervention in pre-school children are needed
Qualitative Evidence	Children’s lived experience of AR therapy, preferences, and barriers are unreported	Mixed-methods studies combining quantitative outcomes with child and caregiver qualitative perspectives are needed

Discussion

This scoping review provides the first comprehensive evidence map of AR-based interventions for hand function in children with CP. Ten peer-reviewed studies were identified, collectively demonstrating that AR-

based rehabilitation is safe, feasible, and associated with improvements across multiple domains of hand and upper extremity function, including range of motion, muscle strength, fine motor dexterity, grip and pinch strength, and functional hand use. These findings are consistent with broader evidence supporting the use of technology-assisted interventions in paediatric rehabilitation.

The most extensively studied dedicated AR system—the WonderTree platform—was associated with significant within-group improvements in upper extremity range of motion, muscle strength, and overall upper extremity function in children with spastic hemiplegic CP across two RCTs.^{18,19} These results are promising given the rigorous study design employed. Touchscreen tablet-based AR (Abd-Elfattah et al., 2024) similarly demonstrated significant improvements in finger dexterity and pinch strength, highlighting the accessibility of lower-cost AR platforms in resource-limited settings.²⁰ Game-based mechatronic devices with AR augmentation (Kanitkar et al., 2023; Peramalaiah et al., 2025) showed improvements in manual dexterity and visual-motor integration, suggesting the added value of combining physical manipulation with digital augmentation.^{21,22}

A consistent finding across all included studies was high child engagement with AR-based interventions and the absence of serious adverse events. This safety profile aligns with findings from broader VR rehabilitation literature in children and supports the feasibility of AR for paediatric use across functional ability levels (GMFCS I–III). The motivational and gamified qualities of AR are particularly relevant in paediatric populations, where maintaining engagement and adherence to high-repetition motor training is a recognised clinical challenge.

For clinicians in paediatric physiotherapy and occupational therapy, this review provides several actionable insights. AR-based interventions appear safe, feasible, and engaging for children with CP across a range of functional abilities. They can be delivered in both clinic-based and home-based formats, and the available evidence supports their use as an adjunct to conventional therapy rather than a standalone replacement. No serious adverse events were reported across any included study.

The choice of AR platform should be guided by the child’s age, cognitive level, functional ability, and the specific impairments being targeted. The WonderTree platform is currently the most evidenced AR system specific to this population. Touchscreen tablet-based AR programmes may offer a lower-cost, higher-accessibility entry point for resource-limited settings. Wearable sensor-based systems and mechatronic devices may be better suited to children with moderate-to-severe

impairments who require haptic feedback to engage meaningfully with the technology.

Physiotherapists utilising AR should be cognisant of the need for individualised goal-setting, integration with the child's occupational priorities, and alignment with the ICF model to ensure that AR-derived gains at the body function level translate to meaningful activity and participation outcomes.

Strengths and Limitations

This review's strengths include its comprehensive database search, adherence to PRISMA-ScR guidelines, transparent eligibility criteria, and use of the PCC framework. Limitations include the broad inclusion of hybrid VR/AR studies in the absence of a sufficient volume of pure AR studies, which introduces conceptual heterogeneity. The scoping review methodology precludes formal quality appraisal or meta-analytic pooling of results. The exclusion of non-English language studies may have introduced language bias. Additionally, the rapid pace of AR technology development means that some included studies' technologies may already be superseded.

Future Research

The most pressing need is for adequately powered, prospective, blinded RCTs that specifically evaluate AR interventions for hand function in children with CP, with standardised outcome measures, long-term follow-up, and reporting guided by TIDieR (Template for Intervention Description and Replication) criteria. Such trials should ideally adopt a core outcome set developed with input from children, caregivers, clinicians, and researchers. There is also a clear need for research in younger (pre-school) age groups, studies in lower-income settings, health economic evaluations, and mixed-methods research incorporating children's perspectives and caregiver experiences.

Conclusion

This scoping review provides the first comprehensive evidence map of AR-based interventions for hand function in children with cerebral palsy. Ten studies were identified, collectively demonstrating that AR-based rehabilitation is safe, feasible, and associated with improvements in upper extremity range of motion, muscle strength, fine motor dexterity, grip and pinch strength, and functional hand use. The evidence base is nascent, with the WonderTree AR platform representing the best-evidenced pure AR system in this population. The field is characterised by heterogeneity in AR system types, intervention parameters, and outcome measures, and is limited by small sample sizes and short follow-up periods.

The growing trajectory towards home-based, sensor-integrated, and gamified AR rehabilitation aligns well with paediatric rehabilitation principles of high repetition, task-specificity, and motivational engagement. There is an urgent need for adequately

powered RCTs with standardised outcome frameworks, long-term follow-up, and cost-effectiveness analyses to establish the evidence base required for widespread clinical implementation. Paediatric physiotherapists are encouraged to explore AR as a complementary tool within a comprehensive, goal-directed rehabilitation programme for children with CP.

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