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Home-Based Telerehabilitation to Prevent Post-Modified Constraint-Induced Movement Therapy Regression in Unilateral Cerebral Palsy: A Randomized Controlled Trial

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ABSTRACT

Aims: To determine the potential of low-end high-intensity home-based hand-arm bimanual intensive therapy (H-HABIT) in mitigating post-modified constraint-induced movement therapy (mCIMT) regression in children with unilateral cerebral palsy (UCP).

Methods: Twenty-two children (aged 4–12 years) with UCP were assigned to either the experimental ($n = 12$) or control group ($n = 10$). Both groups completed 30 h of mCIMT for three weeks, followed by 30 h of H-HABIT for five weeks in the experimental group and none in the control group. Assessments, including the assisting hand assessment (AHA) and other standardized measures, were performed at baseline, post-mCIMT, and post-H-HABIT. Triaxial accelerometers were worn on both wrists during each phase to monitor the activity.

Results: The experimental group showed AHA scores from baseline to post-H-HABIT, with a significant time × group interaction ($p = 0.001$, $\eta^2 = 0.29$) indicating distinct trajectories from the control. In contrast, actigraphy-based measures of the upper limb remained stable over time. Caregiver feedback for H-HABIT showed that 83.33% found the guidelines easy to follow, and 91.67% rated therapist interactions as helpful.

Conclusions: H-HABIT may help prevent post-mCIMT regression. Further research should refine task selection and explore advanced assessment methods to better capture real-world function.

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Modified constraint-induced movement therapy (mCIMT) has been recognized as a potent intervention for improving the functionality and use of the affected upper extremity in children with unilateral cerebral palsy (UCP) (Charles et al., 2006).

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Therapy involves intensive repetitive practice of the affected limb, often accompanied by constraints on the unaffected limb, leading to improved motor function (Taub et al., 2004). Despite its demonstrated effectiveness, the demanding nature and burden of mCIMT (Mancini et al., 2013) have raised concerns regarding its feasibility, tolerability, and long-term adherence. Moreover, some studies have noted a partial regression in functional improvements during post-mCIMT follow-up assessments (DeLuca et al., 2012; Gillick et al., 2018; Sakzewski et al., 2011), posing challenges in preserving the achieved gains.

The mCIMT, which predominantly addresses the affected hand, can be unsuitable for children performing activities of daily living that require both hands, such as dressing and opening bottles (Ouyang et al., 2020). Given that children with cerebral palsy (CP) never experience normal movement patterns due to early brain damage, physical restraint in mCIMT can be mentally taxing and may exacerbate existing bimanual coordination difficulties (Ouyang et al., 2020). This has led to the development of bimanual therapies, such as hand-arm bimanual intensive training (HABIT), introduced in 2006 (Charles & Gordon, 2006), which targets tasks requiring both hands. Numerous hybrid therapeutic strategies that integrate mCIMT with HABIT have emerged (Hoare et al., 2019). For instance, Aarts et al. (2010) found that combining modified CIMT with subsequent bimanual training significantly improved both unimanual and bimanual functions in children with UCP. Similarly, Deppe et al. (2013) demonstrated that a combined protocol, consisting of 60 h of CIMT followed by 20 h of bimanual training, resulted in better isolated motor outcomes than a regimen using only bimanual training. This finding highlights the potential advantages of hybrid approaches over single-method interventions.

However, a key limitation of hybrid approaches is their reliance on high-intensity, short-term protocols, with HABIT alone often requiring more than 30 h per week. Although these intensive interventions can yield short-term functional improvements, they are typically delivered as isolated, time-limited events that may not support lasting changes in the child's everyday life. Some studies have compared continuous therapy durations with more spaced-out sessions over a longer period and reported challenges in maintaining functional gains during follow-up assessments (Brandão et al., 2018), indicating that long-term improvements may be difficult to sustain regardless of the total time spent on therapy if provided in an episodic, event-based manner. Additionally, research on bimanual therapy has shown that increasing the duration of therapy does not always lead to proportionally greater benefits, further drawing into question the efficacy of focusing solely on maximizing the dosage (Sakzewski et al., 2015). Although much of the existing research has focused on the total number of hours of therapy delivered, there is a need to determine the ideal timeframes and intervals for administering these therapies in order to balance their effectiveness with feasibility and long-term adherence.

In this study, we explored the potential of lower-end high-intensity home-based HABIT (H-HABIT) to mitigate post-mCIMT regression. We employed a telerehabilitation framework using video conferencing (Zoom) to deliver H-HABIT sessions in real time, thereby allowing the therapists to the guide caregivers and children in the home setting. H-HABIT was selected because of its practicality and accessibility,

allowing continued therapy in home settings. We hypothesized that H-HABIT would effectively mitigate post-mCIMT regression in Assisting Hand Assessment (AHA) scores. Additionally, we hypothesized that combined mCIMT followed by the H-HABIT protocol would be feasible for families to implement in their home environments over an extended period.

Methods

Design

This study was comprised of a randomized controlled trial with a 1:1 allocation ratio between the experimental and control groups. An independent statistician generated the allocation sequence using permuted block randomization with a block length of four. The research team enrolled participants and assigned interventions with allocation concealment ensured through sealed opaque envelopes. A single-blind design was used to reduce the bias. Outcome assessors who conducted the standardized laboratory assessments were blinded to the group allocation and were not involved in the interventions.

Participants

Twenty-two children (12 boys; mean age 5.48 ± 1.34 years) with UCP due to central nervous system lesions were enrolled in the study, conducted between July 2021 and December 2022 at a tertiary hospital. The participants were recruited through announcements posted in online patient-support communities. They were randomly assigned to either the experimental group ($n = 12$) or control group ($n = 10$) (Figure 1). Recruitment was influenced by the COVID-19 pandemic, which slightly reduced the sample size to 24 participants. The sample size was calculated based on a previous HABIT study (Gordon et al., 2007), indicating that 12 participants per group would be needed to detect a significant difference in AHA scores ($\alpha = 0.05$, $1-\beta = 0.7$). Of the 22 children, seven had participated in a separate CIMT-related study between 2016 and 2018 (child IDs: 1, 2, 3, 4, 5, 17, 19). We opted not to exclude these children because their baseline scores did not differ significantly from those of the participants without prior intensive therapy. The inclusion criterion required a confirmed diagnosis of UCP, whereas the exclusion criteria included severe cognitive dysfunction, untreated seizures, visual or auditory impairment, and musculoskeletal disorders. Sixteen typically developing (TD) children (8 boys, 8 girls; mean age 6.97 ± 2.54 years) were also included for actigraphy comparison. The baseline characteristics of the experimental and control groups are presented in Table 1, and the participant characteristics and neuroimaging findings are shown in Table 2. Informed consent was provided by the parents or legal guardians of all participants. The study was approved by the Institutional Review Board and registered in the Clinical Trials Database (NCT04904796).

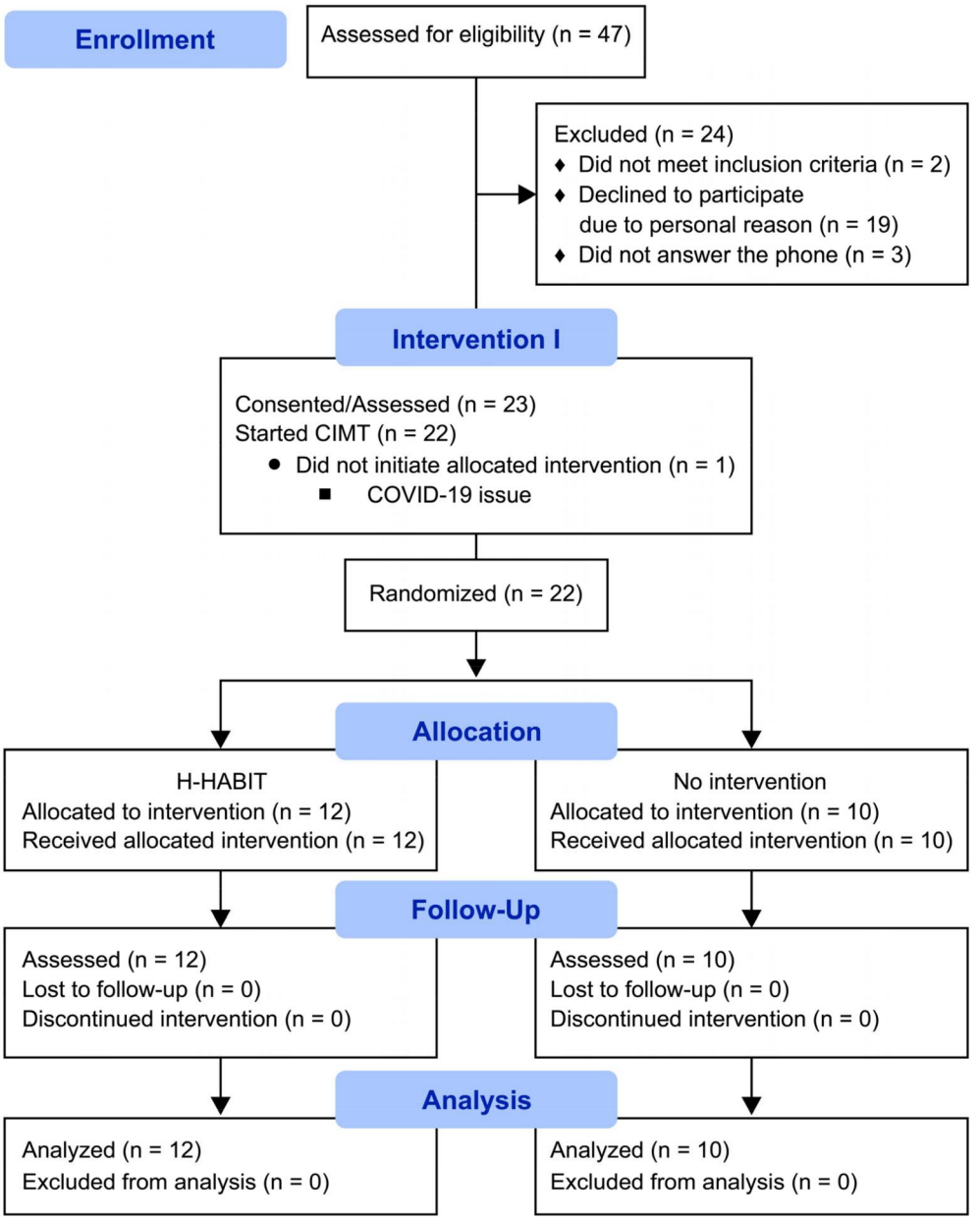

Figure 1. CONSORT 2010 Flow diagram.

Procedures

This randomized controlled trial was performed in two phases: mCIMT and H-HABIT. To maximize the established efficacy at improving unimanual function, mCIMT was initially implemented, followed by the introduction of H-HABIT to translate these gains into improved performance of everyday bimanual activities. All participants initially underwent the mCIMT. The experimental group received H-HABIT, while the control group received no further intervention.

Table 1. Baseline characteristics of each group.

Characteristics		Experimental ($n = 12$)	Control ($n = 10$)	p
Mean (SD) age, years		5.99 (2.36)	4.87 (0.92)	0.149*
Sex, *n* (%)	Male	7 (58.3)	5 (50.0)	1†
	Female	5 (41.7)	5 (50.0)	
MACS level, *n* (%)	1	3 (25.0)	4 (40.0)	0.864†
	2	6 (50.0)	4 (40.0)	
	3	3 (25.0)	2 (20.0)	
Side of involvement, *n* (%)	Right	9 (75.0)	8 (80.0)	r1†
	Left	3 (25.0)	2 (20.0)	
FSIQ (SD)		93.09 (17.06)	80.22 (18.04)	0.123*
AHA (SD), Logits		59.25 (9.25)	61.70 (9.93)	0.560*
PMAL (SD)	How-Often	1.30 (0.58)	1.63 (0.65)	0.240*
	How-Well	2.11 (0.73)	2.05 (0.78)	0.858*
PEDI-CAT (SD)	Daily Activities	53.42 (1.16)	53.20 (1.93)	0.761*
	Mobility	63.92 (2.27)	63.60 (1.58)	0.705*
	Social/Cognitive	65.50 (1.78)	64.20 (2.39)	0.174*
	Responsibility	48.50 (3.39)	47.10 (2.13)	0.254*
MA2 (SD)	ROM	60.49 (16.21)	68.89 (20.45)	0.308*
	Accuracy	66.67 (17.42)	72.00 (19.50)	0.511*
	Dexterity	54.67 (21.65)	57.61 (19.13)	0.739*
	Fluency	58.53 (16.88)	64.76 (20.72)	0.456*
Affected side VMA (SD)		441.52 (163.98)	490.86 (122.89)	0.430*
Less-affected side VMA (SD)		758.24 (203.08)	789.97 (162.27)	0.688*
VMA Ratio (SD)		−0.58 (0.23)	−0.48 (0.21)	0.267*

*Independent *t*-test.
†Fisher's exact test.
AHA: assisting hand assessment; PMAL: pediatric motor activity log; PEDI-CAT: pediatric evaluation of disability inventory computer adaptive test; MA2: Melbourne assessment 2; ROM: range of motion; VMA: vector magnitude average counts.

Each participant underwent 15 sessions (two hours each, five times a week, for a total of 30 h) of mCIMT. This protocol of 30 h in total was selected based on previous research suggesting that this quantity can yield clinically meaningful gains (Sakzewski et al., 2015) while balancing feasibility and caregiver adherence. Several studies have also employed 2-h daily sessions in CIMT protocols (Hoare et al., 2019), supporting our choice of session length. A detachable forearm splint customized for each child was used, with the tasks progressively increasing in difficulty based on the progress and tolerance of each child. Following the clinical sessions, the participants were required to continue using the restraint at home—except during activities such as bathing or sleeping—while the caregivers were instructed to record their daily restraint times. In line with prior CIMT studies, the extent of at-home restraint usage varied considerably in the literature: some required restraint for most of the waking hours or even continuous casting (Hoare et al., 2019), whereas others, similar to our approach, removed the restraint only for bathing or sleeping (Rostami & Malamiri, 2012). Throughout the study period, the participants were not permitted to receive any additional interventions. Additionally, caregivers completed a structured survey to assess their experiences with the mCIMT protocol.

The H-HABIT phase leveraged a telerehabilitation approach based on the methodology of Ferre et al. (2017) and was consisted of 15 sessions (two hours each, three times a week; total: 30 h) over five weeks, conducted *via* Zoom. The sessions were divided into four 30-minute segments focusing on functional tasks, manipulative games, fine motor skills, and gross motor skills. Caregivers, trained using a custom guideline booklet customized by our research team consisting of experienced occupational

Table 2. Participant characteristics and neuroimaging findings.

Child	Sex	Corrected age (y)	Birth term	Group allocation	Basic pattern of damage	Affected hemisphere	Cortical lesion	Involvement of central nuclei
1	M	5.17	Full	Experimental	MCA infarction	L	FR, P	BG
2	F	5.00	Pre	Control	MCA infarction	L	FR, P, T	BG, TH
3	M	5.42	Pre	Experimental	N/A			
4	M	6.50	Pre	Control	MCA hemorrhagic infarction	L	FR, P	BG, TH
5	F	5.00	Full	Experimental	Dysplastic cortex and brainstem, WMDI	L	FR, P, T	TH
6	F	4.42	Pre	Control	HIE	L > R	T, P, O	CR
7	F	9.58	Full	Experimental	MCA hemorrhagic infarction	L	FR, P, T	BG, TH
8	M	4.33	Pre	Control	Hemorrhage	R	FR, P	TH, BG, PO
9	M	4.08	Full	Control	N/A			
10	M	10.58	Pre	Experimental	N/A			
11	F	4.00	Pre	Control	WMDI and hemorrhagic infarction	R	FR, P, T	BG, TH
12	M	9.17	Pre	Experimental	IVH	L	P, T	BG, TH
13	M	4.00	Full	Control	MCA infarction	L	FR, P	TH
14	M	4.17	Full	Experimental	HIE	L	FR, P	BG, TH
15	F	4.50	Full	Control	HIE	L	FR, P, T	TH
16	F	5.08	Full	Experimental	HIE	R	FR	TH, CR
17	F	5.83	Pre	Control	IVH	L	FR, P, O	TH
18	M	4.33	Pre	Experimental	WMDI	R, L	FR	–
19	M	6.00	Full	Control	MCA hemorrhagic infarction	L	FR	BG, TH
20	M	4.00	Full	Experimental	MCA infarction	R	FR, P	BG, TH
21	F	5.42	Pre	Experimental	HIE	R	FR, P, T	BG, TH
22	F	4.00	Full	Experimental	MCA infarction and WMDI	L > R	–	CR

M: Male; F: Female; R: Right; L: Left; FR: Frontal; P: Parietal; T: Temporal; O: Occipital; BG: Basal ganglia; WMDI: White matter damage of immaturity; MCA: Middle cerebral artery; HIE: Hypoxic ischemic encephalopathy; -: No finding; TH: Thalamus; CR: Corona radiata; PO: Pons.

therapists (OTs), prepared the environment for the live session recording. OTs remotely monitored sessions *via* smartphones, providing real-time feedback and adjusting task difficulty based on engagement and tolerance (Figure S1). Throughout the sessions, the OTs recorded any adverse events in real time. Fidelity was ensured through detailed checklists followed by OTs, and adherence was monitored through caregiver logs and remote session supervision. In addition, caregivers completed a structured survey to assess their experiences with H-HABIT implementation. No significant modifications were made to the study protocol.

Measures

Standardized assessments were conducted in a single-blind manner by an occupational therapist with >10 years of experience at baseline (T0), post-mCIMT (T1), and post-H-HABIT (T2).

Pediatric Motor Activity Log

The Pediatric Motor Activity Log (PMAL) evaluates the use of the child's most affected upper limbs during daily tasks, which consist of 22 arm and hand functional tasks, with the collected data being systematically organized. This assessment was evaluated by considering two factors: (1) how-often (PMAL-HO) and (2) how-well (PMAL-HW). The

PMAL has previously demonstrated high test-retest reliability ($r = 0.89$) and internal consistency (Cronbach's $\alpha = 0.93$) (Uswatte et al., 2012).

Pediatric evaluation of disability inventory computer adaptive test

The pediatric evaluation of disability inventory computer adaptive test (PEDI-CAT), a standardized instrument that assesses functional abilities in children with various health conditions, features a 276-item computer-adaptive questionnaire based on caregiver reports covering four domains: mobility, daily activities, social/cognitive function, and responsibility (Haley et al., 2011). In this study, we used the Speedy version of the PEDI-CAT to optimize efficiency. The test-retest reliability for all four domains has been reported as high, with intraclass correlation coefficients (ICC) ranging from 0.96 to 0.99 (Dumas et al., 2012).

Melbourne Assessment-2

Melbourne assessment-2 (MA2) is a unilateral upper limb function test that measures unimanual capacity. This criterion-based assessment evaluated four aspects of upper limb movement quality: range of motion (ROM), precision, dexterity, and fluency. The test comprises 14 unimanual tasks that are video-recorded for subsequent scoring (Randall et al., 2014). The test-retest reliability of MA2 was high (ICC = 0.92–0.98) (Wang et al., 2017).

Assisting Hand Assessment

AHA, our primary outcome measure, is a standardized tool designed for children with UCP. It measures a child's ability to use the affected hand to assist the unaffected hand during various bimanual activities. Assessors review video recordings to score the child's demonstrated capacity to use their weaker arm and hand across 22 items (Holmefur et al., 2009; Krumlinde-Sundholm et al., 2007). The interrater reliability for the sum score has been reported as ICC = 0.98 (two raters) and ICC = 0.97 (20 raters). Additionally, a change of approximately five logits on the AHA has been suggested as the smallest detectable difference (SDD) for children with UCP (Krumlinde-Sundholm, 2012).

Physical Activity

Physical activity data were collected using the ActiGraph wGT3X-BT, tri-axial accelerometer with a dynamic range of ±8 gravitational units and a sampling rate of 30 Hz. Accelerometers were secured to the wrists of the children on both the affected and less affected sides and were programmed to continuously record data for three consecutive days at each assessment time-point (T0, T1, T2), thereby capturing real-world activity outside the intervention setting. This approach aligns with those of previous studies (Coker-Bolt et al., 2017; Goodwin et al., 2020) in which wrist-worn accelerometers have been used to measure upper limb activity in children with UCP. Key actigraphy metrics included the vector magnitude average counts (VMA) and VMA Ratio, which were calculated by taking the natural logarithm (ln) of the ratio between the VMAs of the

affected and less-affected sides. Acceleration data were downloaded and converted into 10-s epochs using the ActiLife 6 software (ActiGraph, Pensacola, FL, USA) and subsequently into activity counts. The TD cohort wore these accelerometers for three consecutive days at monthly intervals.

Data Analysis

Baseline differences between the experimental and control groups were evaluated using t-tests for continuous data and the Fisher's exact test for categorical data. Variables meeting the normality assumptions were processed using two-way repeated-measures ANOVA, whereas those that failed to meet the normality assumptions were subjected to the Friedman test. Post hoc tests for two-way ANOVA and Friedman tests were conducted using the paired *t*-test and paired Wilcoxon signed-rank test, respectively, both with Bonferroni correction. Effect sizes for the ANOVA were captured using the partial eta squared (η^2). SAS (9.4) and R (3.5.0) were used for all analyses. $p < 0.05$ was considered to indicate statistical significance.

Results

Changes in the Standardized Assessments

For the AHA scores, a significant time × group interaction was identified ($p = 0.001$, $\eta^2 = 0.29$). A post hoc analysis revealed significant improvements from T0 to T1 and T2 within the experimental group ($p < 0.05$), indicating sustained progress throughout the study period. Conversely, the control group showed significant improvement only from T0 to T1 ($p < 0.05$), with no further significant changes noted at T2 (Table 3).

In the PMAL, both PMAL-HO and PMAL-HW showed significant time effects ($\eta^2 = 0.57$ and $\eta^2 = 0.53$, respectively) with no significant time × group interactions. Overall, both groups showed notable improvements on PMAL measures without any statistically significant group differences (Table 3).

In the daily activities domain of the PEDI-CAT, a significant time effect was identified ($p < 0.001$, $\eta^2 = 0.29$) but no time × group interaction. Post hoc comparisons revealed no pairwise differences between T0, T1, and T2. The mobility domain, analyzed *via* a Friedman repeated-measures test, showed a significant overall change across time ($\chi^2 = 8.76$, $p = 0.013$). In the social/cognitive (S/C) domain, there was a significant time effect ($p < 0.001$, $\eta^2 = 0.42$) with no significant interaction ($p = 0.660$), and post hoc tests indicated that only the experimental group improved from T0/T1 to T2. The responsibility domain demonstrated neither a significant time effect ($p = 0.080$) nor a significant time × group interaction ($p = 0.180$) (Table 3).

MA2 showed a significant time × group interaction only in the accuracy domain ($p = 0.010$, $\eta^2 = 0.19$). A post hoc analysis revealed that the experimental group improved significantly from T0 to both T1 and T2 ($p < 0.05$), whereas the control group demonstrated significant improvement only from T0 to T2 ($p < 0.05$). No significant time × group interactions were observed in the other MA2 domains (range of motion, dexterity, and fluency) (Table 3).

Table 3. Changes in standardized assessment results across time points.

				Two-way repeated measures ANOVA, two groups × three TS			
				Time effect		Time × group interaction	
	T0, mean (SD)	T1, mean (SD)	T2, mean (SD)	p (η^2)		p (η^2)	
AHA				df = 2; F = 19.03	$p < 0.001$*(0.49)	df = 2; F = 8.01	$p = 0.001$*(0.29)
Experimental	59.25 (9.25)	61.08 (8.54)	63.33 (7.64)		T 0 ≠ 1,2; 1 ≠ 2		T 0–2
Control	61.74 (9.93)	63.10 (10.09)	62.73 (10.56)		T 0 ≠ 1		
PMAL How-Often				df = 2; F = 25.99	$p < 0.001$*(0.57)	df = 2; F = 0.90	$p = 0.420$ (0.04)
Experimental	1.30 (0.58)	2.10 (0.91)	2.37 (0.86)		T 0 ≠ 1,2		
Control	1.63 (0.65)	2.25 (0.57)	2.34 (0.59)		T 0 ≠ 1,2		
PMAL How-Well				df = 2; F = 22.27	$p < 0.001$*(0.53)	df = 2; F = 1.05	$p = 0.360$ (0.05)
Experimental	2.11 (0.73)	2.56 (0.71)	2.99 (0.65)		T 0,1 ≠ 2		
Control	2.05 (0.78)	2.64 (0.64)	2.73 (0.76)		T 0 ≠ 1,2		
PEDI-CAT DA				df = 2; F = 8.01	$p < 0.001$*(0.29)	df = 2; F = 0.42	$p = 0.660$ (0.02)
Experimental	53.42 (1.16)	53.83 (1.40)	54.33 (1.87)		NS		
Control	53.20 (1.93)	53.60 (2.01)	53.80 (1.81)		NS		
PEDI-CAT Mobility				df = 2; χ^2=8.76	$p = 0.013$*		
Experimental†	63.50 (62.00;65.25)	64.00 (63.00;66.00)	66.00 (63.75;66.25)		NS		
Control†	63.00 (62.00;64.00)	63.00 (62.00;64.00)	63.00 (62.25;64.75)		NS		
PEDI-CAT S/C				df = 2; F = 14.30	$p < 0.001$*(0.42)	df = 2; F = 0.43	$p = 0.660$ (0.02)
Experimental	65.50 (1.78)	65.50 (1.83)	66.58 (2.28)		T 0,1 ≠ 2		
Control	61.50 (2.12)	61.70 (2.00)	62.40 (2.07)		NS		
PEDI-CAT RE				df = 2; F = 2.71	$p = 0.080$ (0.12)	df = 2; F = 1.77	$p = 0.180$ (0.08)
Experimental	48.50 (3.39)	48.75 (3.49)	49.75 (2.49)		NS		
Control	46.03 (2.13)	47.01 (3.50)	46.50 (3.98)		NS		
MA2 ROM				df = 2; F = 27.78	$p < 0.001$*(0.58)	df = 2; F = 0.05	$p = 0.950$ (0)
Experimental	60.49 (16.21)	65.74 (16.95)	67.28 (16.47)		T 0 ≠ 1,2		
Control	68.89 (20.45)	74.44 (18.60)	76.30 (18.90)		T 0 ≠ 1,2		
MA2 Accuracy				df = 2; F = 28.87	$p < 0.001$*(0.59)	df = 2; F = 4.77	$p = 0.010$*(0.19)
Experimental	66.67 (17.42)	76.22 (15.74)	79.22 (15.98)		T 0 ≠ 1,2		T 0–1, 0–2
Control	72.00 (19.50)	75.60 (16.49)	77.20 (19.14)		T 0 ≠ 2		
MA2 Dexterity				df = 2; F = 24.86	$p < 0.001$*(0.55)	df = 2; F = 1.05	$p = 0.360$ (0.05)
Experimental	54.67 (21.65)	62.04 (20.09)	66.96 (17.45)		T 0 ≠ 1,2; 1 ≠ 2		
Control	57.61 (19.13)	67.24 (16.82)	67.37 (19.29)		T 0 ≠ 1,2		
MA2 Fluency				df = 2; F = 31.60	$p < 0.001$*(0.61)	df = 2; F = 0.58	$p = 0.570$ (0.03)
Experimental	58.53 (16.88)	62.90 (17.27)	66.09 (16.42)		T 0 ≠ 1,2; 1 ≠ 2		
Control	64.76 (20.72)	68.10 (20.70)	70.48 (19.80)		T 0 ≠ 1,2		

*Significant value.
†Friedman repeated measures, with median and interquartile range.
AHA, assisting hand assessment; PMAL, pediatric motor activity log; PEDI-CAT, pediatric evaluation of disability inventory computer adaptive test; MA2, Melbourne assessment 2; ROM, range of motion; DA, daily activities; S/C, social/cognitive; RE, responsibility.

Table 4. Changes in actigraphy results across time points.

				Two-way RM analysis of variance, two groups × three TS			
				Time effect		Time × group interaction	
	T0, mean (SD)	T1, mean (SD)	T2, mean (SD)	p (η^2)		p (η^2)	
CP cohort							
Affected Side VMA				df = 2;F = 1.41	$p = 0.261$ (0.07)	df = 2; F = 0.76	$p = 0.472$ (0.04)
Experimental	441.52 (163.98)	488.85 (183.20)	487.67 (176.73)		NS		
Control	490.86 (122.89)	507.54 (125.29)	486.78 (82.44)		NS		
Less-Affected Side VMA				df = 2;F = 0.53	$p = 0.590$ (0.03)	df = 2; F = 0.47	$p = 0.630$ (0.02)
Experimental	758.24 (203.08)	799.61 (216.46)	797.32 (209)		NS		
Control	789.97 (162.27)	794.96 (152.38)	782.99 (122.23)		NS		
VMA Ratio				df = 2;F = 1.83	$p = 0.170$ (0.08)	df = 2; F = 0.54	$p = 0.590$ (0.03)
Experimental	−0.58 (0.23)	−0.53 (0.25)	−0.54 (0.24)		NS		
Control	−0.48 (0.18)	−0.46 (0.21)	−0.48 (0.20)		NS		
TD cohort							
VMA Ratio							
TD children	−0.08 (0.04)	−0.08 (0.05)	NA	$t = 0.453$	$p = 0.657$*	NA	NA

*Paired t-test.

TS: testing session; TD: typically developing; NS: not significant; VMA: vector magnitude average counts; NA: not applicable.

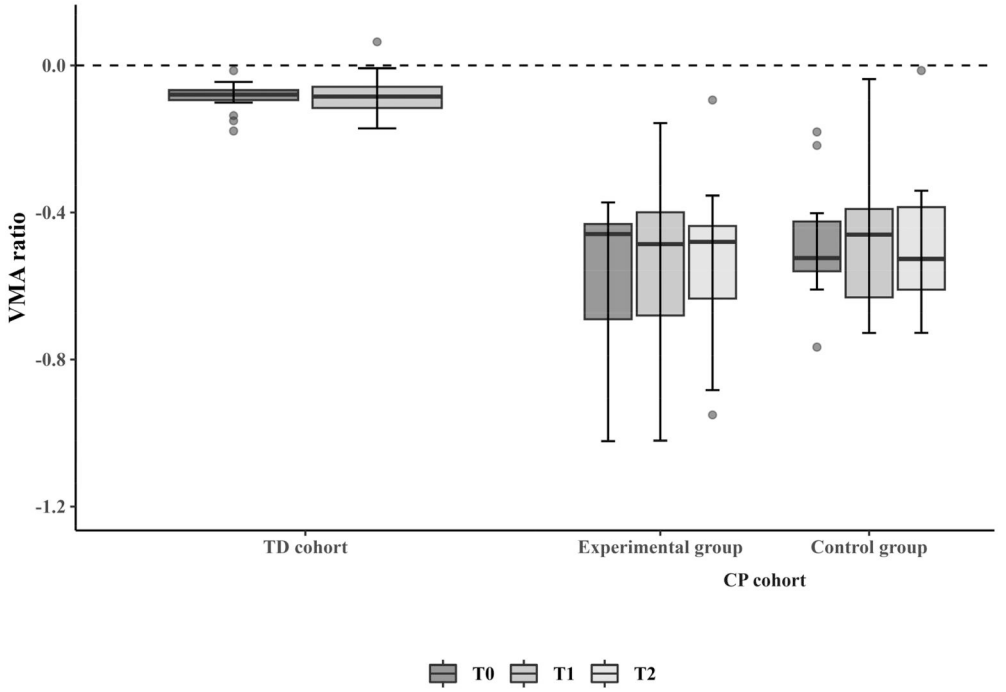

Figure 2. Changes in VMA ratios over time. Box plot showing temporal changes in the VMA ratio. The TD cohort data were collected monthly at T0 and T1. The CP cohort assessments were performed at T0, T1 (post 3-week CIMT), and T2 (post 5-week H-HABIT, experimental group only).

Changes in the Actigraphy Variables

VMA values for the affected and less-affected sides, along with the VMA ratio, did not differ significantly over time or between groups (Table 4). In the experimental group, the affected side VMA moved only slightly from 441.52 (163.98) at T0 to 488.85 (183.20) at T1 and 487.67 (176.73) at T2, while the VMA ratio stayed around −0.58 to −0.53. The control group's affected side VMA fluctuated minimally around 490.86 (122.89) at T0 to 507.54 (125.29) at T1 and 486.78 (82.44) at T2, with a stable ratio of approximately −0.48. TD children consistently showed a ratio near −0.08 (Figure 2).

Caregiver Feedback and Adverse Events

Caregiver feedback on the mCIMT protocol was mixed, with 54.55% finding it easy to follow and 45.45% reporting difficulties. A significant proportion (54.55%) also emphasized the importance of continuous restraint use at home, with the average daily restraint time recorded at 9.92 h (SD = 2.33). Additional insights can be drawn from the results presented in Table S1.

For H-HABIT, most caregivers (83.33%) found the custom booklet guidelines to be easy to understand. Approximately 75% reported feeling comfortable with the required technology, while 91.67% rated real-time interactions with therapists as "very helpful." All caregivers acknowledged the importance of the activities in the H-HABIT sessions;

the schedule was manageable for the majority (83.33%), and 75% recommended treatment. Further details on the caregivers' responses are provided in Table S2.

Discussion

While previous studies have clearly reflected the growing interest in hybrid CIMT (hCIMT) (Aarts et al., 2010; Boyd et al., 2013; Case-Smith et al., 2012; Deppe et al., 2013), our study offers a fresh perspective on hCIMT in children with UCP, adhering to the standard structure of the initial mCIMT, followed by HABIT. Our approach differed in the extent of H-HABIT duration, which was extended to 5 wk compared with the usual 1–2-week span employed in previous studies. Furthermore, while other intensive protocols often involve up to 6 h per session, our patient-centric approach involved 30 h of therapy over five weeks. Impressively, this reduced intensity did not compromise compelling outcomes. Our AHA scores showed a significant time effect ($p < 0.001$ [0.49]), coupled with a notable time × group interaction ($p = 0.001$ [0.29]). These results emphasize the efficacy of our elongated yet mellower H-HABIT approach.

Although the experimental group showed better outcomes than the control group in AHA scores, the improvements did not surpass the SDD of five logits (Krumlinde-Sundholm, 2012), with an increase of 2.25 logits following H-HABIT in this study. This finding aligns with those of previous studies (Ferre et al., 2017; Sakzewski et al., 2015), highlighting the ongoing challenge of achieving clinically relevant improvements in children with UCP despite the use of intensive protocols. Indeed, previous research repeatedly demonstrated modest changes below clinically meaningful thresholds, underscoring the inherent difficulty of achieving substantial functional gains in this population. This limitation may result from factors such as insufficient specificity or personalization of therapy tasks, which often rely on structured repetitive exercises rather than tailored meaningful activities that are closely aligned with each child's daily life. A possible direction for future interventions could involve incorporating task selection that aligns more closely with children's daily routines, motivations, and environmental contexts to help facilitate meaningful functional improvements. Nevertheless, the current study's approach focusing on sustainable long-term therapy in home settings remains clinically relevant as it provides a practical foundation for integrating therapeutic strategies into everyday life despite its lower intensity.

We observed a significant improvement in MA2 accuracy, with a notable time × group interaction ($p = 0.010$, $\eta^2 = 0.19$). A group difference emerged between T0 and T1, although both groups underwent mCIMT during this phase. The reasons for this finding are unclear. However, the experimental group included slightly older participants, which may have influenced their engagement. While one study suggested that the efficacy of CIMT is not necessarily age dependent (Gordon et al., 2006), older children may have been better able to participate in intensive CIMT programs, with group dynamics and collaboration potentially enhancing their motivation and engagement (Gilmore et al., 2010). In addition, the lower baseline MA2 scores in the experimental group may have allowed for greater improvements through CIMT. Nevertheless, the relationship between the severity of initial impairment and the response to CIMT remains unclear. Although several RCTs and CCTs involving children with varying impairment levels have demonstrated positive outcomes following CIMT, the impact of

baseline severity on treatment response remains uncertain (Eliasson et al., 2014). Future studies should investigate whether baseline characteristics influence CIMT outcomes.

Our hypotheses on feasibility were partially supported. Although the mCIMT phase was effective, caregiver feedback indicated significant challenges, with 45.45% of caregivers reporting difficulties, largely because of the requirement for continuous restraint at home, which averaged 9.92 h daily. Previous qualitative research demonstrated that caregivers consistently report constraints outside clinical settings as the most burdensome aspect of mCIMT implementation (Mancini et al., 2013). To our knowledge, evidence supporting the additional therapeutic benefits of continuous daily restraint outside intensive clinical practice sessions remains limited. Indeed, Eliasson et al. (2014) explicitly indicated that no study has directly compared these two approaches, highlighting a critical gap in current knowledge and an important area for future investigations. Thus, our findings underscore the importance of structuring future mCIMT protocols to minimize home-based constraint burdens while preserving therapeutic effectiveness.

In contrast, the H-HABIT phase was more positively received, with 83.33% of caregivers finding the guidelines clear and 75% recommending treatment. Our telerehabilitation approach, delivered *via* videoconferencing, allowed families to avoid additional travel burdens and schedule sessions more flexibly, enhancing their adherence. However, as highlighted by Sia et al. (2024), telerehabilitation efforts often encounter barriers such as unreliable internet connections, inadequate informational technology support, limited private space, and insufficient technological familiarity among both providers and clients. These hurdles can prolong sessions, hinder rapport-building, or challenger families with limited internet access. Thus, researchers should be mindful of possible unintended negative impacts when designing such interventions. To minimize these potential negative effects, future interventions should consider flexible scheduling, individualized caregiver support, and regular check-ins to ensure that families are not overwhelmed.

It is worth noting that the experimental group ultimately received a total of 60 h of intervention (30 h of mCIMT plus 30 h of H-HABIT), whereas the control group received 30 h of mCIMT alone. Consequently, the difference in total dosage (60 h vs. 30 h) should be considered when interpreting the results, as a higher cumulative dose may partially explain the observed improvement in the experimental group. This supports the findings by Sakzewski et al. (2015), who reported that 30 h of upper-limb therapy might be insufficient to induce sustained motor gains, whereas 60 h produced more robust effects. Nonetheless, our primary objective was to investigate whether extending therapy beyond a standard 30-h regimen could preserve or enhance mCIMT gains in a feasible, home-based format. Future studies could employ dose-matched comparators or stratified designs to further clarify the distinct benefits of add-on bimanual therapy versus the effect of simply increasing the total dosage.

In the daily activities domain of the PEDI-CAT, no statistically significant changes were detected in either group, possibly owing to the relatively low dosage used herein. However, a recent report by Ramey et al. (2021) indicated that children who received 30 h of therapy with cast usage showed a 1.7-point increase in PEDI-CAT daily activities domain, whereas those receiving 60 h demonstrated a smaller net change of 0.9 points, suggesting that a higher dosage does not necessarily yield proportionally greater gains.

In our study, the experimental group ultimately received 60 h of combined mCIMT and H-HABIT; hence insufficient intervention time alone may not fully account for the lack of improvement in the daily activities domain. Another possibility is that, although our protocols were task-oriented, the activities (e.g. simple cutting or folding paper) were relatively generic and not consistently tailored to each child's unique home routines, potentially limiting everyday functional carryover. Notably, the social/cognitive domain of children in the experimental group showed an unexpected increase from the post-mCIMT to final assessment, which may reflect the role of H-HABIT in fostering greater confidence, self-initiated engagement, or caregiver–child interactions—factors that can indirectly enhance social participation. Moreover, the remote format might have promoted additional communication, prompting children to seek help or collaborate more frequently with their caregivers and therapists, thereby reinforcing social facets of task performance.

The actigraphy results revealed no significant changes in the measured variables before and after the mCIMT and H-HABIT. This observation aligns with findings from prior research (Goodwin et al., 2020), suggesting that improved capacity through interventions, such as CIMT, does not translate to measurable differences in real-world upper-limb use. Although mCIMT and H-HABIT are task-oriented in principle, our protocol largely focused on general activities such as simple cutting or folding paper, rather than personalized tasks aligned with each child's daily routines. However, an increase in arm movement measured by actigraphy does not necessarily equate to enhanced everyday functioning. Performance in daily life involves myriad contextual, motivational, and environmental factors, and actigraphy alone may be unable to capture more subtle or individualized gains. Therefore, future research might explore advanced measurement approaches, such as human activity recognition—a technique combining sensor fusion and machine learning to identify specific tasks and contextual factors—(Vrigkas et al., 2015) to gain more nuanced insights into how children with UCP use their affected arms in routine activities, or consider other more effective methods of evaluating individualized improvements.

Study Limitations

This study had several limitations. First, the modest sample size limits the generalizability of our observations. Second, the utilization of accelerometers, while progressive, presents challenges in discerning between intentional and incidental limb movements, such as arm sway during walking. This limitation could have introduced variability in our movement data, making them less reflective of the intentional upper limb activity. Third, the total dose of therapy differed between the experimental (60 h) and control (30 h) groups, which may confound the isolated effect of adding bimanual training versus simply increasing the overall therapy time. Finally, our follow-up period was relatively short, in part due to the coronavirus disease 2019 pandemic constraints that made long-term in-person assessments challenging. Consequently, as this study served primarily as a pilot investigation focused on short-term effects, it may not have fully captured the enduring impact or long-term benefits of the interventions. The regression of motor function after CIMT may take several months to emerge (DeLuca et al., 2012;

Sakzewski et al., 2011), further underscoring the need for extended follow-up periods in future research to determine whether the gains observed herein are sustained over time.

Conclusion

The results of our evaluation of a 30-h, low-end high-intensity H-HABIT regimen following mCIMT highlight the potential of this approach to maintain the therapeutic gains achieved through initial mCIMT, potentially preventing post-mCIMT regression. The extended H-HABIT duration, which differs from the typical short-term intensive schedules used in previous studies, appears to be a promising strategy for long-term management. However, these improvements did not translate into significant gains in real-world daily activities or actigraphy measures. The limited dosage and lack of individualized task-specific interventions that closely aligned with children's everyday routines may have constrained the extent of functional carryover. Thus, future research should explore refining the therapy content through personalized approaches, appropriately increasing the dosage, and targeting specific daily routines to better enhance everyday performance and functional outcomes.

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