

## CASE REPORT

# Voluntary-assisted Upper Limb Training for Severe Cerebral Palsy Using Robotics Devices and Neuromuscular Electrical Stimulation: Three Case Reports

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**Background:** Constraint-induced movement therapy (CIMT) improves the motor function of paralyzed upper limbs of adults after stroke. However, in patients with severe spastic cerebral palsy (CP), the use of CIMT is not warranted. Our aim was to investigate the feasibility and effectiveness of repetitive voluntary-assisted upper limb training (VAUT) for three patients with severe CP using a combination of robotics [Hybrid Assistive Limb (HAL)] and functional electrical stimulation [Integrated Volitional Control Electrical Stimulation (IVES)]. **Case:** Three patients with CP were enrolled. Patients 1, 2, and 3 were 8-, 19-, and 18-year-old males, respectively. Patient 1 had spastic hemiplegia, while patients 2 and 3 had spastic quadriplegia. VAUT using single-joint HAL was performed for 1 or 2 sessions/month for 50 min/session over an 8-month period for 9–13 sessions in total. One patient's voluntary hand movement was insufficient, affecting his upper limb exercise performance; therefore, IVES was required in addition to HAL. Outcome measures included motor function of the upper limbs and use of paralyzed hands, which were measured before and after intervention. No adverse events were observed during VAUT. After intervention, the Action Research Arm Test scores showed improvements in all three patients. The Children's Hand-use Experience Questionnaire showed improvements in two patients. **Discussion:** The use of VAUT, together with new systems such as HAL and IVES, for severe CP is safe and may be effective. Our study suggested that upper limb function can be improved for patients with severe CP.

**Key Words:** functional electrical stimulation; hybrid assistive limb; robotic device; upper limb exercise

## INTRODUCTION

Cerebral palsy (CP), a typical childhood-onset disease, is a lifelong neurological disorder that primarily impairs motor function secondary to disturbances in the developing fetal or infant brain.<sup>1)</sup> In patients with CP, a variety of movements are reduced, and selective motor control becomes difficult be-

cause abnormal movement patterns are strengthened as their primitive reflexes remain uncontrolled.<sup>2,3)</sup> When spastic paralysis occurs in the upper limbs, it becomes difficult to manipulate objects and tools in daily living activities (playing, learning, leisure activities, eating, changing clothes, etc.). In addition, the more affected limb tends to be disregarded. In CP patients, rehabilitation is important to improve affected

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**Table 1.** The Manual Ability Classification System

Level	Description
I	Handles objects easily and successfully
II	Handles most objects, but with somewhat reduced quality and/or speed of achievement
III	Handles objects with difficulty; needs help to prepare or modify activities
IV	Handles a limited selection of easily managed objects in adapted situations
V	Does not handle objects and has severely limited ability to perform even simple actions

From Eliasson *et al.*<sup>8)</sup>

upper limb function, activities of daily living, and quality of life.

Constraint-induced movement therapy (CIMT) is a rehabilitation method aimed at improving the motor function and increasing the use of the affected upper limb in daily life for adults who have suffered a stroke.<sup>4,5)</sup> In patients with CP, the effectiveness of CIMT has been reported.<sup>6,7)</sup> CIMT consists of intensive and repetitive exercise using only the affected upper limb while the non-affected upper limbs are constrained. However, whether patients are able to perform CIMT by grasping, transporting, and releasing objects using only the affected hand depends on the remaining function of the affected hand. The Manual Ability Classification System (MACS) is a measure for evaluating the upper limb function of activities of daily living with CP (**Table 1**).<sup>8)</sup> In cases of severe CP with MACS levels III and IV, the upper limb tasks of CIMT that can be performed are limited because patients have difficulty moving their wrist and fingers. In such cases, CIMT cannot be effectively performed, and, unfortunately, there has been no successful intervention method for severe CP that does not meet the criteria for CIMT. Shierk *et al.* reported that CIMT is the most commonly reported therapeutic intervention to improve upper limb function for MACS level II, and the majority of participants across studies were MACS level II.<sup>9)</sup> Therefore, more research is needed on specific interventions for other severe MACS levels.

Currently, robot-assisted training is attracting attention in the field of adult and pediatric rehabilitation. The Hybrid Assistive Limb<sup>®</sup> (HAL; Cyberdyne, Tsukuba, Japan) is a novel wearable robot that can assist patients based on the intended movements of the wearer.<sup>10)</sup> When a single-joint-type HAL device (HAL-SJ; HAL-FS01) is used for the upper limbs, patients can repeat the flexion/extension movements of the elbow joint. Improvement of upper limb function using HAL-SJ has only been reported in adult patients.<sup>11,12)</sup> For patients with CP, use of HAL-SJ has been reported to reduce muscle co-contraction and improve upper limb function and performance of activities of daily living (ADL) by using

simple exercises such as repeat flexion/extension movements of the elbow joint.<sup>13)</sup> However, in the previous report, only simple exercises such as elbow flexion and extension were performed using HAL-SJ. With regard to training using HAL-SJ, to the best of our knowledge, there has been no report on its combination with other therapies, such as CIMT.

Similar to HAL, neuromuscular electrical stimulation (NMES) has demonstrated its effectiveness in the neurorehabilitation of patients with stroke presenting with upper limb paralysis.<sup>14)</sup> An example of NMES is the use of Integrated Volitional Control Electrical Stimulation (IVES, OG Giken, Okayama, Japan), which outputs intense electrical stimulation in direct proportion to the amplitude of the voluntary monitor electromyogram (EMG) of the target muscles.<sup>15)</sup> It has been reported that NMES therapy using IVES is an effective treatment for patients with stroke presenting with severe upper limb paralysis.<sup>16)</sup>

In this case series, we performed voluntary-assisted upper limb training (VAUT) to improve upper limb function and increase the frequency of its use in daily living. These patients presented with CP with severe upper limb paralysis and did not meet the criteria for CIMT. Our VAUT used a combination of HAL and IVES depending on the degree of upper limb paralysis. Our method is expected to improve upper limb function and ADL ability even in patients with severe CP. Our study is novel because we used upper-limb-type robots instead of the lower limb types and we tested these devices in pediatric patients.

## CASE

### Participants

Three patients with CP were enrolled in this study between May 2018 and January 2019 (**Table 2**). All patients and their parents provided written informed consent for the publication of individual patient data. One patient had spastic hemiplegia, whereas the other two had spastic quadriplegia. Using the MACS, one patient was classified as level III and

**Table 2.** Patient characteristics

Participant	1	2	3
Age (years)	8	19	18
Sex	M	M	M
Height (cm)	122	157	152
Weight (kg)	23	50	53
Etiology	CP	CP	CP
Paralysis type	Hemiplegia	SQ	SQ
Severe affected side	L	R	R
MACS	III	IV	IV
Brs (upper limb)	IV	III	III
Brs (finger)	V	IV	IV
GMFCS	I	IV	III
CFCS	I	I	I

SQ, spastic quadriplegia; L, left; R, right.

two patients were classified as level IV.<sup>8)</sup> The Brunnstrom stage (BrS) of the upper limb of the more affected side was III in two patients and IV in one patient. Finger BrS was IV in two patients and V in one patient.<sup>15)</sup> Patients 2 and 3 were unable to fully extend the metacarpophalangeal (MP) and interphalangeal (IP) joints at 10°, and the wrist at 20°. Case 1 met the CIMT criteria, but Cases 2 and 3 did not. Cases 1, 2, and 3 showed scores on the modified Ashworth Scale of 0, 2, and 1+, respectively, for the elbow flexor muscle. Cases 1, 2, and 3 had a Gross Motor Function Classification System (GMFCS) level of I, IV, and III, respectively<sup>17)</sup>. All patients were level I on the Communication Function Classification System (CFCS). The study used the following inclusion criteria: (i) MACS level II–IV; and (ii) the ability to express pain and anxiety through language, facial expressions, and gestures. The exclusion criteria were as follows: (i) patients who experienced difficulties in wearing HAL because of joint deformation/contracture; (ii) patients who did not cooperate and those who had difficulty following our instructions because of mental disabilities; (iii) patients whose upper limb did not fit in the devices used; (iv) patients who underwent botulinum toxin treatment in the previous 3 months; and (v) patients who had complications with a high level of risk management for physical therapy (severe hypersensitivity and marked ataxia).

Patient 1 was an 8-year-old male who presented with left hemiplegia caused by CP. He performed ADL using his non-paralyzed side, the shoulder of his paralyzed side, and his mouth as a substitute for his left hand.

Patient 2 was a 19-year-old male who presented with spastic quadriplegia caused by CP and severe right upper

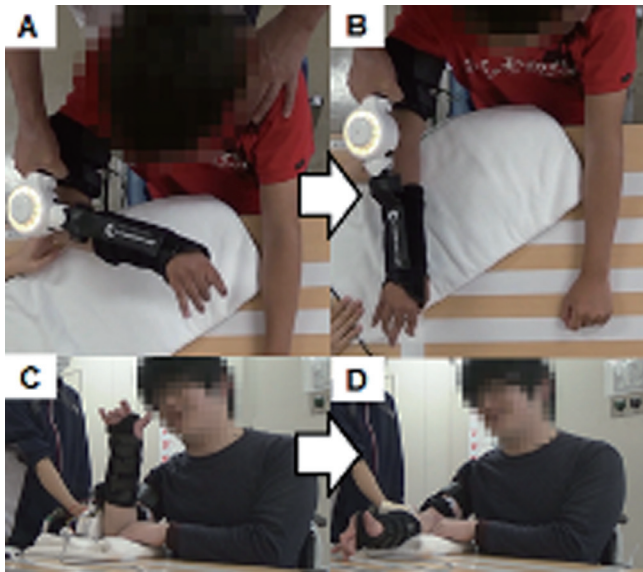
limb paralysis. The patient used an electric wheelchair for transportation. His shoulder flexion and abduction of active movements were 100°. Wrist dorsiflexion, extension of the MP and proximal interphalangeal (PIP) joint, and abduction of the thumb could be performed simultaneously, but separate upper limb movement was difficult. In addition, hypertonia muscle tonus was present during upper limb exercise. Therefore, he was fixed in a position of head right rotation, shoulder elevation with internal rotation, and pronation of the forearm.

Patient 3 was a 18-year-old male who presented with spastic quadriplegia caused by CP and severe right limb paralysis. He used an electric wheelchair for transportation. At the age of 17 years, he underwent orthopedic surgery of the upper limb; however, his voluntary upper limb movement was still insufficient. His shoulder flexion and abduction of active movements were 100°. He could achieve slight dorsiflexion of the wrist joint along with slight extension of the MP and PIP joint. He could not grasp objects because of difficulty in voluntary thumb abduction.

### Therapy Device and Intervention

We performed VAUT using HAL-SJ for 1 or 2 sessions/month for 50 min/session over an 8-month period for a total of 9–13 sessions. We planned an intervention protocol of at least 8 sessions over an 8-month period. During this training, patients wore a HAL. The HAL-SJ uses a bio-electrical signal (BES)-based control system and demonstrates joint torque assist with the wearer's voluntary drive. The HAL was attached to the side with greater paralysis of the upper limbs (patient 1, left limb; patients 2 and 3, right limb). First, training of repetitive elbow flexion/extension exercises during shoulder adduction and 90° shoulder abduction were performed 50–100 times each (**Fig. 1**). Subsequently, upper limb task practice was performed based on CIMT.<sup>18)</sup> Task practice was performed for five or six activities (reaching with shoulder, elbow movements using sticks and blocks, pinching, and gripping of coins and marbles). For each task, the level of difficulty, such as the number of items, speed, height, and shape of objects, was adjusted in a stepwise manner depending on the patient's ability, which was based on the function of the paralyzed hand. In addition, as ADL practice, activities such as eating (spooning beans) and washing (hanging and folding a towel) were performed according to the abilities of the patients (**Fig. 2**). We also advised patients to perform task practice at home by themselves or with their family.





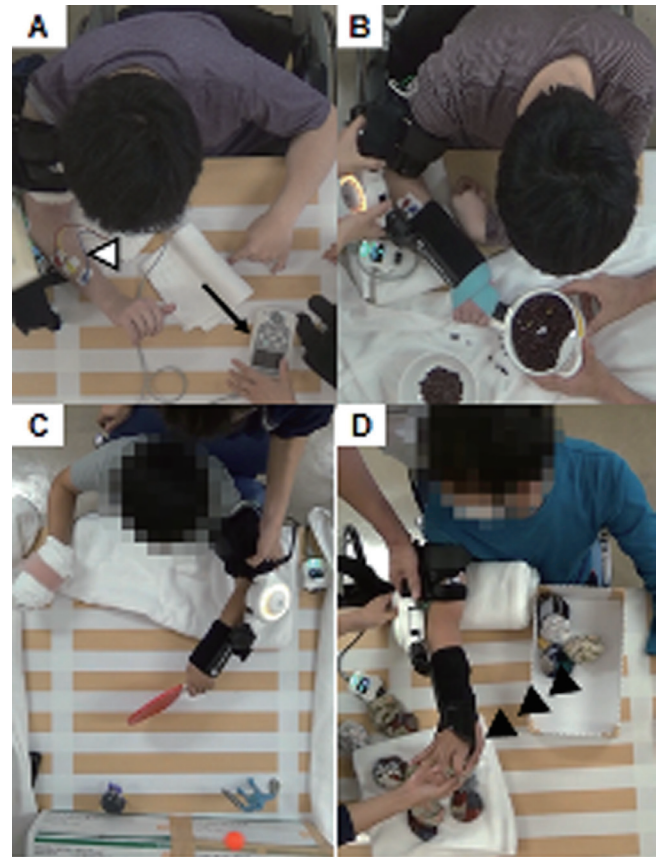
**Fig. 1.** A, B: Patient 2 performs upper limb training of repetitive elbow flexion (A)/extension (B) exercise at shoulder 90° flexion with the Hybrid Assistive Limb® (HAL; Cyberdyne, Tsukuba, Japan). C, D: Patient 3 performs upper limb training of repetitive elbow flexion (C)/extension (D) exercise at shoulder adduction with HAL and Integrated Volitional Control Electrical Stimulator (IVES, OG Giken, Okayama, Japan).

### Outcome Measures

The Action Research Arm Test (ARAT)<sup>19</sup> and Quality of Upper Extremity Skills Test (QUEST)<sup>20</sup> were used to compare upper limb functions within 1 week pre- and post-intervention. In addition, for patients 1 and 2, we interviewed the patients' mothers using the ABILHAND-Kids<sup>21</sup> and Children's Hands-Use Experience Questionnaire (CHEQ; CHEQ 2.0, <http://www.chcq.se/questionnaire>)<sup>22</sup> regarding the use of paralyzed hands for ADL. The study protocol was approved by the ethics committee of Ibaraki Prefectural University of Health Sciences (approval number: 797; date of approval: 28 December 2017; approval update: approval number: e356; date of approval: 8 June 2022).

## RESULTS

All three patients received 50-min sessions of HAL for 1 or 2 sessions/month over an 8-month period for 9–13 sessions in total. No adverse events were observed during VAUT. For patient 3, IVES was used in combination with HAL-SJ. The control mode of the HAL-SJ was Cybernic Voluntary Control (CVC)—Gentle mode. The gain settings were adjusted



**Fig. 2.** A: Patient 3 performs adjusted IVES output during finger movement. Arrowhead shows an electrode with extensor carpi radialis and extensor digitorum communis; arrows show the IVES body. B: Patient 3 practices scooping adzuki beans with a spoon from a bowl while wearing HAL and IVES. C: Patient 1 wears HAL and practices hitting a ping-pong ball with a table tennis bat to knock down a toy figure. D: Patient 2 wears HAL and practices grasping and moving small beanbags from a box.

within the ranges of 5–40, 20–100, and 30–100 for patients 1, 2, and 3, respectively. The assist level was 1, 1–8, and 1 for patients 1, 2, and 3, respectively. The torque limit was adjusted within the ranges of 30%–40%, 50%–60%, and 50%–60% for patients 1, 2, and 3, respectively. The difficulty of the task varied according to patient ability. For example, the shape of the object to be handled was gradually made more difficult or the moving range of objects was expanded.

The ARAT results increased from 31, 9, and 17 points before the intervention to 49, 20, and 20 points after the intervention in the paralyzed hands of patients 1, 2, and 3, respectively. Comparing the subordinate items, increased scores were observed for grasp, grip, pinch, and gross move-

**Table 3.** Change in measurements before and after voluntary-assisted upper limb training

Assessment	Score (min–max)	Subject						
		1		2		3		
		Pre	Post	Pre	Post	Pre	Post	
ARAT score (R/L)	0–57	57/31	57/49	9/52	20/57	17/54	20/54	
ARAT subscore	Grasp	0–18	18/11	18/15	3/18	7/18	6/18	6/18
	Grip	0–12	12/7	12/11	3/12	5/12	5/12	7/12
	Pinch	0–18	18/6	18/14	0/13	3/18	0/15	0/15
	Gross movement	0–9	9/7	9/9	3/9	5/9	6/9	7/9
QUEST total score	0–100	75.1	82.8	40.0	58.5	41.0	49.9	
QUEST subscore	Dissociated movements	0–100	85.9	89.1	68.8	76.6	53.1	56.3
	Grasp	0–100	37.0	66.7	18.5	44.4	25.9	40.7
	Weight bearing	0–100	94.0	92.0	34.0	52.0	46.0	64.0
	Protective extension	0–100	83.3	83.3	38.9	61.1	38.9	38.9
ABILHAND-Kids (logits)		1.752	1.752	–0.164	–0.164	-	-	
CHEQ 2.0	Grasp efficacy	0–100	25	26	0	0	-	-
	Time utilization	0–100	28	30	41	41	-	-
	Feeling bothered	0–100	32	32	42	45	-	-

ments. The QUEST scores increased from 75.1, 40.0, and 41.0 points before the intervention to 82.8, 58.5, and 49.9 points after the intervention in patients 1, 2, and 3, respectively. Comparing the subordinate items, increased scores were observed for dissociated movements, grasp, weight bearing, and protective extension.

Regarding the use of paralyzed hands in daily living, we interviewed patients' mothers using the ABILHAND-Kids and CHEQ for patients 1 and 2. The ABILHAND-Kids scores showed no change before and after intervention in both patients. However, the CHEQ score after intervention was increased from 25 to 26 points in "grasp efficacy" for patient 1, from 28 to 30 points in "time consumption" for patient 1, and from 42 to 45 points in "feeling bothered" for patient 2 (Table 3).

The following issues were identified in task practice: for patient 1, it was difficult to maintain motivation because of the subject's young age. Therefore, we tried to maintain motivation by introducing game elements, such as table tennis and coin arrangement (Fig. 2C). For patient 2, compensatory movements, such as head rotation and shoulder elevation were seen during VAUT, and the patient complained of fatigue. Therefore, the assist gain and extension/flexion balance of the HAL-SJ were adjusted for each task so that compensatory movements did not frequently occur during VAUT. For patient 3, voluntary wrist joint dorsiflexion, finger extension, and thumb abduction direction were limited. In addition, the assistance provided by using HAL-SJ alone was

limited by the shape and size of the object used in the task. Therefore, IVES was used in combination with the extensor muscles of the forearms to supplement voluntary hand and finger movements, while HAL-SJ assisted the elbow joints and IVES assisted with finger extension simultaneously. For this patient, we used the power-assist mode with a minimum power of 15%–25%, a maximum power of 35%–50%, and a sensitivity of 2.5–2.9. By adjusting HAL-SJ and IVES, thumb abduction and finger extension became possible, and the patient was able to perform fine tasks, such as pinching and gripping, and the range of task practices expanded (Fig. 2).

## DISCUSSION

In this study, patients with severe CP were able to perform and repeat normal joint movements frequently over an extended period (50 min) by using a device with new methods of assisting with voluntary movements, such as HAL and IVES. To promote brain plasticity, it is desirable for the patient to perform voluntary and repeated movements, such as during CIMT.<sup>23,24</sup> In this study, in addition to supporting elbow joint movements using HAL, it became possible to assist hand movements using IVES. Accordingly, even for patient 3, who had severe CP, it was possible to perform fine tasks of the upper limb requiring voluntary finger movement. As a result, this patient succeeded in upper limb training by handling various objects, similarly to patients 1 and 2. In

a previous study of upper extremity assessments soon after stroke, minimal clinically important differences of 12 and 17 points were given for ARAT.<sup>25)</sup> The ARAT score in the paralyzed hands of patients 1, 2, and 3 increased by 18, 11, and 3 points from before the intervention, respectively. These cases cannot be compared in general because the patients have CP, but the effect of this intervention was suggested in patient 1, who was the youngest and had the mildest level of paralysis of the three patients.

There have been many reports of robot-assisted gait training of the lower limbs, but studies regarding its effectiveness in the upper limbs are limited.<sup>26)</sup> In previous reports using HAL-SJ, the training was limited to simple movements such as elbow flexion and extension, and there are no reports of upper limb training with combined movements of the shoulder, elbow, and finger, as in this study.<sup>11,12,26)</sup> In our patients, upper limb function and ADL ability improved through upper limb task practice using HAL, indicating its effectiveness. Moreover, for patient 3 with severe CP, who had insufficient ability to move his wrist and perform finger extension, we performed an intervention using a combination of IVES and HAL. IVES can increase agonist muscle activities by providing electrical stimulation when muscle activity occurs, which can assist with voluntary movement, similar to HAL. Improvement of voluntary finger movement ability and upper limb function has been reported in patients with severe hemiplegia, who had difficulty performing dorsiflexion of the wrist, after treatment by CIMT combined with IVES.<sup>27)</sup> Even for patients with CP, it was safe to perform upper limb task practice while assisting with voluntary movement of the fingers using IVES.

Upper limb function and ADL performance improved, similar to a previous report on CIMT for patients with CP. Abd El-Kafy *et al.*<sup>28)</sup> and DeLuca *et al.*<sup>29)</sup> reported that the exercise efficiency of patients with hemiplegic CP improved by performing CIMT for 3–4 weeks for 3–6 h/day. Our study demonstrated improvements in upper limb function and ADL performance despite low-frequency intervention of only once or twice a month in outpatient settings. Moreover, in previous reports using HAL-SJ, the training was limited to simple movements, such as elbow flexion and extension, and there have been no reports of upper limb training using the HAL-SJ for the elbow joint during task practices in various limb positions as demonstrated in the present study.<sup>12,13)</sup> Therefore, this intervention was more effective because training focused on functional improvements by promoting brain plasticity through the use of HAL or IVES in assisting the voluntary movements of patients. In this study, VAUT

using a combination of HAL and IVES was extremely effective as a new rehabilitation method. VAUT may provide a new breakthrough for functional improvements in patients with CP with severe upper limb spastic paralysis.

This study has some limitations. First, only three cases were included in our study; therefore, the generalizability of findings may be limited. Furthermore, the small sample size did not allow for statistical analysis. Second, this study was performed without a control group and did not compare the frequency of the intervention and implementation period. In the future, it will be necessary to elucidate the mechanisms of functional improvement by assessing brain organizational changes using techniques such as transcranial magnetic stimulation and diffusion magnetic resonance imaging.

## CONCLUSION

VAUT using new systems such as HAL and IVES for patients with severe CP was safe and effective. The HAL was able to increase normal elbow joint movement of the paralyzed side under voluntary movement even for patients with severe upper limb paralysis who did not adequately fit the CIMT criteria. By combining IVES to assist with voluntary dorsiflexion of the wrist joint/finger extension, patients with more severe CP could perform fine upper limb exercises. VAUT using a combination of HAL and IVES according to the severity of paralysis may improve upper limb function and use of the affected hand in the daily life of patients with severe CP. In the future, it is expected that new small-sized devices will be developed to assist with the voluntary movements of young patients with severe CP in the early stages of development.

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## CONFLICTS OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare no competing interests.

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