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Ankle Control and Strength Training for Children with Cerebral Palsy using the Rutgers Ankle CP

A case study

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***Abstract*— The purpose of the study described here was to develop and feasibility test the Rutgers Ankle CP, aimed at ankle strengthening and improved control for children with cerebral palsy (CP). The system was an upgrade in hardware (new foot attachment, new robot controller) and software (new games and programming language) of the earlier Rutgers Ankle in order to permit training of children with CP. The new Rutgers Ankle CP was used to train ankle strength and motor control in a 7 year old boy with CP during 36 rehabilitation sessions (12 weeks, 3 times/week). Assessments for impairment, function and quality of life were taken before and after training. Results indicated improvements in both strength and motor control. Gait function improved substantially in ankle kinematics, speed and endurance. Overall function (GMFM) indicated improvements that were typical of other ankle strength training programs. Quality of life increased beyond what would be considered a minimal clinical important difference. While these results are only for a single participant, they are very encouraging toward improving the function and quality of life of children with cerebral palsy. Further research with a larger number of participants is planned.**

Keywords- cerebral palsy, Rutgers Ankle CP; ankle strengthening, ankle control;

I. Introduction

Cerebral palsy (CP) is a non-progressive disorder with impaired motor function secondary to injury of the immature brain [1]. Cerebral palsy is the most prevalent physical disability originating in childhood with an incidence of 2-3 per 1,000 live births [2]. Only the central nervous system (CNS) is initially damaged in CP, and this is often due to intra-ventricular hemorrhage and periventricular leukomalacia. Despite this localized CNS trauma, damage is eventually seen peripherally with growth and development in the muscles, bones, and joints of the extremities. Manifestations include: 1) lack of selective muscle control, 2) dependence on primitive reflex patterns for ambulation, 3) abnormal muscle tone, 4) relative imbalance between muscle agonists and antagonists across joints, and 5) deficient equilibrium reactions [3]. These manifestations result in poor gait, diminished function and reduced quality of life.

Muscle weakness, or the lack of strength, is a primary impairment in children with CP [4, 5]. Specifically at the ankle, both the dorsiflexors and plantarflexors are weaker by about 30 to 35% in children with CP, when compared to children without disability. Muscle weakness is a concern when considering procedures to improve the function of children with CP since many of the current treatments further weaken the muscles. However, recent results indicating that increases in ankle or knee strength after training can improve gait and function in children with CP have been reported [6, 7]. No cure exists at this time for CP, but many treatments are used to improve gait and function. These include tendon lengthenings, transfers, releases, selective dorsal rhizotomy, Botulinum toxin, Baclofen, stretching, casting, orthotics and robotic rehabilitation. The Anklebot, developed at MIT, is a 3-DOF wearable robot, backdriveable with low intrinsic mechanical impedance, and weighs about 3.6 kg [8]. Its dimensions are meant for adult populations, and its weight may be problematic for patients which present with weak lower extremities. The first paediatric trial aimed to determine the feasibility of robotic-assisted treadmill training in children with central gait impairment was done on the pediatric Lokomat (Hocoma AG, Switzerland) – a two-leg driven orthotic exoskeleton adjustable to the anatomy of a patient [9]. Patients' gait improved significantly when they practiced walking on a treadmill while partially un-weighted.

Virtual reality is known for its engaging, highly motivating characteristics when used in therapy [10-12]. The first virtual rehabilitation system developed for the ankle was the Rutgers Ankle [13], consisting of a small Stewart platform-type parallel pneumatic robot, combined with custom rehabilitation videogames written in WorldToolKit [14]. This earlier system was used successfully by patients chronic post-stroke and by those with musculoskeletal deficits [15, 16]. This pioneering work was followed by a controlled study on patients with chronic stroke, in which robotic rehabilitation integrating our custom rehabilitation games on the Rutgers Ankle, was shown to be clinically more beneficial than robotic rehabilitation on

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the Rutgers Ankle in the absence of the video games [17]. A recent study on the Lokomat showed that pediatric patient motivation was maintained by the introduction of virtual reality game-like environments [18]. The purpose of the study described here was to develop and feasibility test the Rutgers Ankle CP, a follow-up version of the Rutgers Ankle, aimed at ankle strengthening and improved control for children with cerebral palsy.

II. METHODS

A. Case description

The participant was a 7 year old child diagnosed with mild ataxic cerebral palsy. His birth history was unremarkable. He had difficulty with speech, no cognitive delays and ambulated independently. The participant wore bilateral shoe inserts for pronation and trips/falls were a daily occurrence. He received physical, occupational and speech therapy in school once weekly, which was allowed to continue during this study.

The participant was recruited through word of mouth after the study was approved by the Institutional Review Boards of Washington University in St. Louis (WUSTL) and of Rutgers University. The intervention took place at the Human Performance Laboratory (WUSTL) in 2010.

B. Data collection instruments

There were two outcome data collection sessions, pre- and post-intervention. The participant was consented before any data were collected. Data from 7 clinical outcome measures were collected by a senior physical therapist (SR) who is a co-author of this paper. These outcome measures were: 1) strength [19], 2) motor control [20], 3) Gross Motor Function Measure (GMFM) [21], 4) maximum ankle dorsiflexion at initial contact during gait [21], 5) gait speed [21], 6) six minute walk test [22], and 7) quality of life using the Pediatric Quality of Life Inventory PedsQL [23, 24]. A Kincom dynamometer (Chattanooga Group, Inc., Chattanooga, TN, Model, 125E+) was used for assessing ankle strength [19]. Maximum effort dorisflexion (Max DF) and plantarflexion (Max PF) concentric torque values were recorded over a full range of motion at 90^{o}/s. The averaged right and left maximum values were the outcome variables. Ankle motor control was quantified by having the participant attempt to dorsi- and plantarflex his ankles "in-phase" and "anti-phase" in time to a metronome (60 Hz) [20]. Lag time (s) of the left relative to the right ankle for both in-phase and anti-phase were used as the outcome measures. A lag time of zero would indicate perfect "in phase" or "anti-phase" movement between the right and left sides. Gait speed and ankle dorsiflexion angle at initial contact (DF@IC) were quantified using a typical gait analysis video motion capture system (Motion Analysis Corp, Santa Rosa, CA, Model, Eagle Camera) [21]. The walk-run-jump domain for the GMFM was used to assess overall function [21]. The Gross Motor Function Measure (GMFM) is a standard criterion-referenced test designed to assess change in gross motor function in children with CP [25]. The 88 items of the test (GMFM-88) assess activities in five dimensions: 1) lying and rolling, 2) sitting, 3) crawling and kneeling, 4) standing, and 5) walking, running and jumping. Each item is scored using a 4-point Likert scale (0=does not initiate; 1=initiates; 2=partially completes; 3=completes). A child's totals from each category are divided by the total possible points for that category, to produce a category percentage score (maximum being 100%). These percentages can be used individually or can be averaged to yield an overall score. The distance walked during a 6-minute walk test was used to assess gait endurance [22]. Finally, the summary scaled score for the child and parent portions of the Peds QL were used to assess quality of life in the participant [7]. The PedsQL utilizes a child self-report (ages 5-18) and parent proxy-report (ages 2-18) to measure the core dimensions of health as delineated by the World Health Organization [23, 24]. It includes 23 items that measure the physical, emotional, social and school functioning of children and adolescents. The reliability of the total score is excellent (α = 0.88 child, 0.90 parent report). The measure has been shown to be valid distinguishing between healthy children and children with acute and chronic health conditions. The threshold for clinical significance (minimal improvement) is 4.5 points for the parent report and 4.4 points for the child report.

In addition to clinical outcome data, the computer running the rehabilitation games collected game performance data. These data included various variables that were game dependent (for example the speed of an avatar object controlled by the patient, or game scores). These data were sampled transparently many times per second during each game and stored for later analysis. When plotted over time, game variables give an indication of patient's performance, and indirectly of ankle strength and control.

C. The Rutgers Ankle CP system

The Rutgers Ankle CP robot represents the interface that allows the patient to interact with the simulator, by using the ankle. The therapy is in the form of engaging games that need to respond promptly to the patient's input. To achieve the best system response, and thus patient's experience, the rehabilitation system has been upgraded from the earlier Rutgers Ankle, as described below.

The experimental system used in this study is shown in Fig. 1. It incorporates a multi-core PC workstation running the custom games (simulator), a large display, a Stewart platform robot, a new robot controller box and a rehabilitation chair.

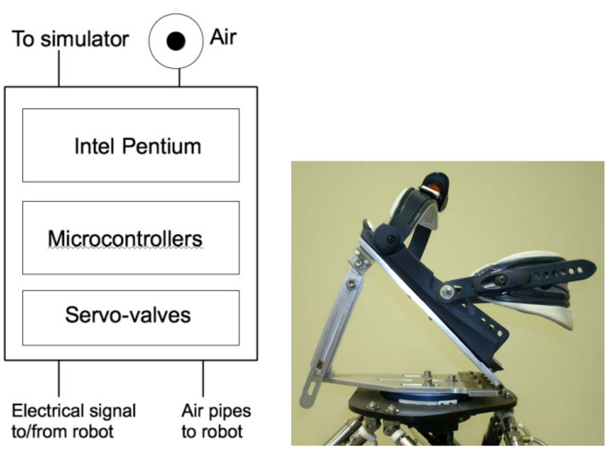
1) Description of new controller

The new controller box was completely redesigned, creating a more powerful reaction force, more accurate direct kinematics, added inverse kinematics for passive training, less air consumption. The new hardware (Fig. 2a) combines an Intel dual core processor with microcontrollers to drive the air servo-valves at a control loop frequency of 200Hz. The controller software is developed in Java running on a Linux OS, as opposite to the old controller that was developed in C++ running on DOS. The communication between the robot controller box and the simulator workstation is done over a 128 kbps serial line. Network communication is also available

Figure 1. The Rutgers Ankle CP system installed at the clinical site. © Rutgers Tele-Rehabilitation Institute and WUSTL. Reprinted by permission.

for higher transfer rates, but not necessary at this stage of the project.

The top platform of the robot has a snowboard foot binding which allows safe and easy attachment to the patient's foot. Unlike the earlier system where the binding was parallel to the top platform, the Rutgers Ankle CP has an ankle angle adapter (Fig. 2b). The adapter, weighing about 1 kg, was designed and fabricated out of aluminum, to permit a more comfortable seating of the participant while playing the games. The adapter assembly was attached to the top platform of the Rutgers Ankle CP and the snowboard binding was in turn attached to the adapter. The net effect was that the patient's foot was kept at a 45° to 90° relative to the horizontal. For the new system, two robots were manufactured by a small mechanical machine shop according to Rutgers design. One robot was used in the study and the other was provided as a spare. It should be noted that while the robot had the capability to train for ankle eversion and inversion, for simplicity or to limit the degrees of freedom, it was decided not to include that in the protocol.



a) b)

Figure 2. Hardware modifications: a) the new controller block diagram; b) ankle angle adapter. © Rutgers Tele-Rehabilitation Institute and WUSTL. Reprinted by permission.

2) Rehabilitation games

The games running on the simulator are a very important part of the system. If the games are engaging the patient will play longer and maintain focus, resulting in better outcomes. At the same time, the games should be safe for patient and should measure and log the performance improvements. Based on these logs, the therapist can adjust the game parameters to make the games more challenging.

The system software components running on the workstation are: the Scheduler, the session Baseline, and the *Airplane* and *Breakout 3D* games. The software is developed in Java and Java3D API, running on a Windows OS.

The Scheduler module allows the therapist to define the games sequence and progression for each patient. The order and the parameters for each game can be set and saved. Also the session time and rest periods can be controlled.

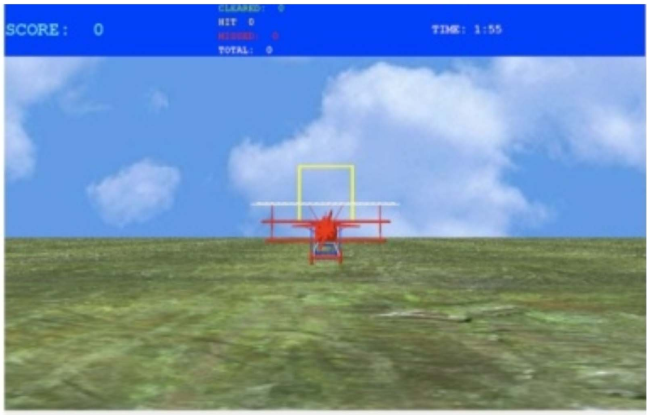
Each session starts with a baseline. It measures the ankle mobility for the current rehabilitation session based on four parameters: inward, outward, upward and downward. The previous session values are shown, thus motivating the patient to exceed these limits. The ankle excursion in plantarflexion and dorsiflexion is used to adapt the games to the patient, in a given day.

In the *Airplane* exercise (Fig. 3a) the patient, pilots a virtual airplane through target frames colored yellow (for visibility). The position of the frames follows a curve path with hills and valleys. The game score is based on the number of frames clearly passed (100 points for a clear pass, -25 points for the plane hitting the frame, and -75 for a frame completely missed). At the beginning of the exercise the following parameters can be chosen: airplane velocity, air turbulence, scene visibility, and exercise time. When the haptic function is on, and a target frame is hit by the piloted airplane, the patient feels a fast up and down movement of the robot platform.

The *Breakout 3D* exercise (Fig. 3b) was initially developed for arm rehabilitation [26] on our prototype Rutgers Arm system. It was subsequently ported to the Rutgers Ankle CP system, such that the game avatar is a paddle controlled by the ankle and not the forearm. The ankle movement controls the paddle to bounce the ball thus destroying a wall of bricks, one brick at a time. The length of paddle, the brick size in the wall and the ball speed can be set at the beginning of the exercise. The score is incremented by 1 for each brick destroyed. The number of balls when missed by the paddle and leaving the table is counted and saved as a performance parameter. For this training the games were set to exercise just the ankle dorsiflexion and plantarflexion. The haptic feedback in the *Airplane* game was not used.

D. Intervention

The participant trained for 36 sessions (three times per week for 12 weeks) on the Rutgers Ankle. A warm up was performed at the start of each training session and consisted of 2 minutes of walking. Next, the participant was seated



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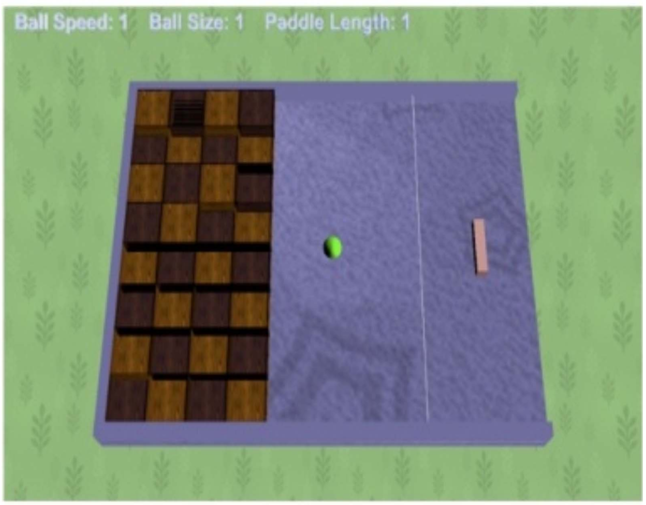

b)

Figure 3. Game starting screens: a) *Airplane* game, b) *Breakout 3D* game in the configuration used to train the right ankle.

comfortably on a rehabilitation chair, secured in place using a pelvic strap and a mid-thigh strap on the exercising extremity. The knee joint was positioned at approximately 90º of flexion and the active ankle range of motion limits in dorsiflexion and plantarflexion were established.

The participant then exercised on the Rutgers Ankle CP by playing the *Airplane* and the *Breakout 3D* games. A large computer screen was placed directly in front of the participant. The *Airplane* game allowed the participant to use ankle dorsiflexion and plantarflexion to pilot the plane up and down through target squares on the screen. Target accuracy was recorded as the number of targets correctly cleared, targets hit and targets completely missed. There were 3 variables to manipulate; airplane speed, visibility and turbulence. The *Breakout 3D* game allowed the participant to use ankle dorsiflexion and plantarflexion to move a paddle up and down on the screen to strike a moving ball that would in turn take out a single block in a block wall. Accuracy was recorded as success rate in the percentage of blocks successfully removed from the wall, and the number of balls used to do so. The variables to be set included ball speed and paddle length. A single game lasted approximately 5 minutes; each game was alternated two times per side (left ankle and right ankle) for a total training time of at least 40 minutes/session. Training was progressed using the variables for each game. For example the first session of the *Airplane* game was at 100% visibility, 0% turbulence and 25% speed. Once the participant missed 0 targets and hit <3 targets, the speed was progressed to 50%. By the final session the participant was training at 0% visibility (dark with storms), 75% turbulence and 100% speed. For the first session of the *Breakout 3D* game, the ball speed was at level 1, paddle length at level 1 and block size at level 1. By the final session, the participant was training with a ball speed at level 6, paddle length at level 2 (shorter paddle) and block size at level 2 (smaller blocks). Note that the therapy the child was receiving before beginning participation in the current study was continued during the experimental intervention.

III. OUTCOMES

A. Clinical Outcomes

Clinical outcomes are summarized in Table I.

B. Computer Gaming Performance

A sample of gaming data progression collected over the length of therapy is presented in Fig. 4. For the *Airplane* game the graph plots scores for each ankle trained vs. airplane avatar speed. For the *Breakout 3D* game, the graph plots scores for each ankle, vs. ball speed.

C. Acceptance of the technology

The participant was highly motivated, compliant and very engaged with progression of the variables to the next level. The participant was anxious to have additional game levels and more games to play. He was also interested in developing his own games.

TABLE I.
CLINICAL OUTCOME ASSESSMENTS TAKEN PRE- AND POST-INTERVENTION.

Assessment	**Pre-intervention**	**Post-intervention**
	Strength	
Max DF (Nm/kg)	0.21	0.50
Max PF (Nm/kg)	2.10	2.37
	Motor Control	
In-Phase (s)	-0.69	0.10
Anti-Phase (s)	0.76	0.42
	Gait	
DF@IC (º)	-4	5
Speed (cm/s)	98.7	120.0
6 min walk (m)	508	556
	GMFM	
-wrj (%)	94.4	98.6
	Peds QL	
Child	85.7	91.4
Parent	79.3	85.0

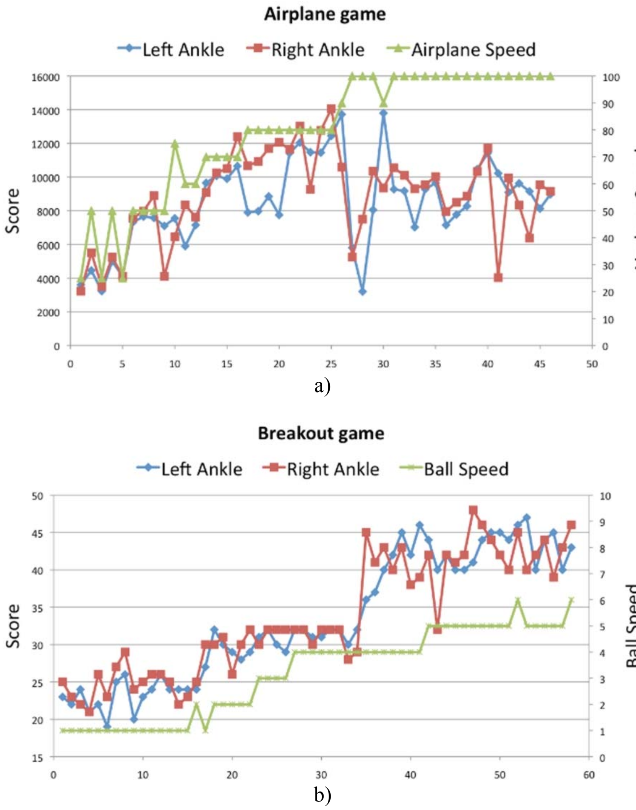

Figure 4. Game performance data: a) *Airplane* game score vs. airplane avatar speed; b) *Breakout 3D* game score vs. ball speed. © Rutgers Tele-Rehabilitation Institute and WUSTL. Reprinted by permission.

D. *Quality of life outcomes*

The PedsQL reports filled by the parent and child show a posti-intervention increase of 5.7 points each. Based on the instrument's 4.5 points threshold for minimal clinical important difference reported in literature [23], the improvement in the participant's quality of life has clinical significance.

IV. DISCUSSION

The underlying strategies for the intervention were four-fold. The first was related to brain plasticity where current theory suggests that hundreds of repetitions are necessary to bring about changes in motor patterns [27]. The second was the overload principle where muscles are trained under conditions in which they do not typically function and they respond to the demand [28]. The third strategy was motivation. We believed the games would motivate the child to such an extent that he would perform ankle movement repetitions under load in order to successfully play the game. Finally, the fourth strategy was that improvement in basic control of the ankle would be transferred to the functional tasks of gait and overall function (i.e., GMFM). With this final strategy, games that simulated basic walking patterns were not part of the protocol.

The increase in strength of the plantarflexors (0.27 Nm/kg) was less than those previously recorded for trained plantarflexor muscles (0.4 Nm/kg) in children training for the same amount of time on a Kincom dynamometer [21]. The increase in strength of the dorsiflexors (0.29 Nm/kg) was slightly larger than those previously recorded for trained dorsiflexor muscles (0.22 Nm/kg) in children training on the Kincom dynamometer [7]. Our goal for the motor control test was to quantify a learning transfer that we believed would take place as a function of the intervention. For the In-Phase results, there was essentially no change in motor control as the right ankle lagged behind the left during the pre-intervention test and the left lagged behind the right during the post-intervention test. However, the anti-phase results showed much improvement from pre- to post intervention. A perfect anti-phase would have 0.0 sec time lag. Even though the ankles were not trained in a reciprocal manner, the lag time post- (0.42 sec) was about half of pre- value (pre- 0.76 sec), indicating the participant had improved coordination of right and left ankles.

Gait improvements were seen for all three measures. Ankle kinematics indicated good progress with a 9^{o} angle at initial contact improvement. There was substantial increase of 21 cm/s in gait speed. While pre-training gait speed values (91$\pm$22 cm/s) were in the range of other children with CP, post-intervention gait speed was in the range of children without disability (113$\pm$18 cm/s) [21]. The six minute walk test also improved with the training on the Rutgers Ankle CP. The 48 m increase in the distance walked by the participant post-intervention is greater than the change that might occur from one test to another (~18 cm/s) [25]. The four point improvement in the GMFM was about the same as that previously reported in children training for the same amount of time on a Kincom dynamometer [7].

Looking at the game performance data several things become apparent. In the first half of the intervention there is a good correlation between the increase in airplane avatar speed and the patient's scores. Once the airplane speed was set to maximum, however, there is an initial drop in scores, indicating the patient missed more target squares. Scores then increase again, indicative of adaptation, before dropping in the last sessions. This increase in missed gates is probably due to the degradation of the visual feedback from the simulation, since in these sessions the frequency of storms and fog were increased. These setting in turn reduced the time given the patient to aim for the next target, demanding an increase in ankle control and reduced reaction time. The trend is apparent in both ankles. Looking at the *Breakout 3D* data, it is evident that the ankle control improved over the therapy, resulting in progressively higher scores. This positive trend is maintained by both ankles, and for repeated increase in ball speed over the length of intervention. Again the patient adapted to these faster balls, which he was able to bounce and win the game despite controlling shorter paddle avatars. Overall the patient demonstrated improved ankle speed and "eye-ankle" coordination, a trend that was characteristic of both ankles.

Children as young as 4-6 years old may be able to perform this task. They need to be able to follow commands such as "push down on your toes to make the plane move down so it can go through a target". The training sessions required direct supervision from a therapist for setup and progression of each game depending on the child's performance. The patient was motivated to exercise for the required duration and there was good compliance with the protocol. Once maximum game difficulty was attained, the patient wanted to be challenged more and expressed a desire for new games. In general, and based on prior research [29], it is believed that lengthy game-based interventions of pediatric populations need to constantly introduce new games, so to maintain participant's motivation.

V. CONCLUSIONS

The Rutgers Ankle CP was used to train (12 wks, 3 x/wk) for ankle strength and motor control in a 7 year old boy with CP. Assessments for impairment, function and quality of life were taken before and after training. Results indicated improvements in both strength and motor control. Gait function improved substantially in ankle kinematics, speed and endurance. Overall function (GMFM) indicated improvements that were typical of other ankle strength training programs. Quality of life increased beyond what would be considered a minimal clinical important difference. While these results are only for a single participant, they are very encouraging toward improving the function and quality of life of children with cerebral palsy. Further research with a larger number of participants is planned, as well as providing like devices at the clinic and home.

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