Use of Virtual Reality to Improve Upper-Extremity Control in Children With Cerebral Palsy: A Single-Subject Design

Yu-Ping Chen, Lin-Ju Kang, Tien-Yow Chuang, Ji-Liang Doong, Shwn-Jan Lee, Mei-Wun Tsai, Suh-Fang Jeng, Wen-Hsu Sung

Background and Purpose

Virtual reality (VR) creates an exercise environment in which the intensity of practice and positive feedback can be systematically manipulated in various contexts. The purpose of this study was to investigate the training effects of a VR intervention on reaching behaviors in children with cerebral palsy (CP).

Participants

Four children with spastic CP were recruited.

Method

A single-subject design (A-B with follow-up) was used. All children were evaluated with 3 baseline, 4 intervention, and 2 follow-up measures. A 4-week individualized VR training program (2 hours per week) with 2 VR systems was applied to all children. The outcome measures included 4 kinematic parameters (movement time, path length, peak velocity, and number of movement units) for mail-delivery activities in 3 directions (neutral, outward, and inward) and the Fine Motor Domain of the Peabody Developmental Motor Scales–Second Edition (PDMS-2). Visual inspection and the 2-standard-deviation–band method were used to compare the outcome measures.

Results

Three children who had normal cognition showed improvements in some aspects of reaching kinematics, and 2 children's change scores on the PDMS-2 reached the minimal detectable change during the intervention. The improvements in kinematics were partially maintained during follow-up.

Discussion and Conclusion

A 4-week individualized VR training program appeared to improve the quality of reaching in children with CP, especially in children with normal cognition and good cooperation. The training effects were retained in some children after the intervention.

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The term "cerebral palsy" (CP) describes a group of movements and posture that are attributed to nonprogressive impairments in the developing fetal or infant brain.[1] Approximately half of children with CP may sustain dysfunctions in upper-extremity (UE) activities such as reaching, grasping, and manipulation.[2] When compared with reaching in children who are developing typically, reaching in children with CP is jerkier, slower, less forceful, and less straight.[3–5] Current therapeutic interventions for UE control in children with CP have emphasized repeated practice of functional activities in various contexts with sufficient feedback (ie, augmented information).[6–9] However, children with CP tend to show difficulty in repeated practice of functional activities because of their movement limitations or a lack of variability in intervention contexts.[9–11]

Virtual reality (VR) is a computer technology that creates a virtual context and objects that allow for interactions with users.[12,13] This technology provides an alternative intervention program for helping to manage UE problems in children with CP.[14] Virtual reality creates an exercise environment in which the intensity of practice and positive visual and auditory feedback can be precisely and systematically manipulated in various nearly natural environments to allow for individualized training in motor learning.[14,15] Furthermore, VR provides a 3-dimensional spatial correspondence between the degree of movement in the real world and the degree of movement observed on the computer screen. Such a spatial representation allows for visual feedback relating to knowledge of performance and guidance, which are crucial for motor learning in children with CP.[13,14] Recently, VR was explored as a training device for improving motor performance in children with CP.[16,17] To date, only one case study[16] has examined the effectiveness of VR for improving UE function in children with CP.

Reid[16] used a VR play-based system to train 4 children with spastic CP and aged between 8 and 12 years. Children with CP received one VR training session per week; each session lasted 1.5 hours. The intervention session mainly focused on using arm movements to interact with objects on the computer screen. Outcomes were measured with the Quality of Upper Extremity Skills Test (QUEST) and an item in the Bruininks-Oseretsky Test of Motor Proficiency that required touching a swinging ball with the preferred hand. Two of the 4 children with CP showed minimal improvements in the QUEST score, whereas all 4 children showed increases in the number of successful contacts in touching the swinging ball. Overall, the children were found to have a high degree of motivation for, interest in, and opportunity for engaging in play activities during the intervention. The results of that case study suggested that VR training may motivate children with CP to engage in repeated practice of reaching behaviors. However, the limited efficacy of VR for improving UE function may be related to the outcome measure (ie, QUEST) not being sensitive enough to capture an improvement in reaching in these children. A more sensitive assessment tool, such as kinematic measures, may be more effective for detecting qualitative changes in movements.

The previous findings implicated the potential of using VR as an alternative intervention for children with CP. However, there is still a lack of published literature examining the effectiveness of a VR intervention for improving reaching behaviors in children with CP. The previous case study did not use sensitive outcome measures and did not report improvements over time.[16] Therefore, the purpose of this study was to investigate the training effects of a VR intervention on reaching behaviors in children with spastic CP.

Method

Participants

Four children (3 boys and 1 girl; mean age=6.3 years) with spastic CP participated in this study (Tab. 1). All participants were recruited from the outpatient physical therapy departments of 2 medical centers in Taipei, Taiwan, and volunteered upon hearing of the study. Children were included if they were able to follow verbal instructions in the reaching task, reach forward for more than half of their arm length, and grasp a tennis ball with flexed fingers and if they had normal or corrected-to-normal vision and hearing. All relevant information either was obtained from their medical records or was reported by their physical therapists. Participants were excluded if they had received or were scheduled to receive surgery or botulinum toxin type A injections in the training arm within the preceding 4 to 6 months or during the planned study period or if they had a severe attention deficit, as confirmed from their medical records. Both hands met the inclusion criteria for participants 2 and 3, and the preferred hand (right) was used for VR training and reaching kinematics. Only one hand met the inclusion criteria for participant 1; this hand was the preferred hand (right), and this hand was used for VR training and reaching kinematics. Both hands met the inclusion criteria for participant 4; the right hand was the preferred hand, and the left hand (the affected hand) was used for VR training and reaching kinematics.

The parents of all participants signed informed consent forms approved by the Institutional Review Board at Taipei Veterans General Hospital,

Table 1.
Characteristics of 4 Children[a]

Participant	Age	Sex	Condition	Dominant Hand	Spasticity	Cognition	Visual/Auditory Status
1	6 y 4 mo	Male	Spastic quadriplegia	Right	Mild increase	Within normal range	Myopia/normal
2	8 y 6 mo	Female	Spastic quadriplegia	Right	Mild increase	Within normal range	Astigmatism, strabismus, amblyopia (not corrected with eyeglasses)/normal
3	5 y 3 mo	Male	Spastic quadriplegia	Right	Mild increase	Mild mental retardation	Hyperopia (corrected with eyeglasses)/ normal
4	4 y 8 mo	Male	Spastic hemiplegia	Right	Nearly normal	Within normal range	Normal/normal

[a] Data were obtained from medical records or physical therapists.

and oral consent was obtained from all participants. All participants were familiar with the testing laboratory and instrumentation used in this study because they had participated in another study conducted by the first author (YPC) 4 months earlier. The previous study was done to examine the effects of different task goals (to fit a ball into a small container versus to throw a ball into a big container) on reaching kinematics and did not affect the present study.[18]

Design

A single-subject research design (A-B with follow-up) was used to examine the training effects of the VR intervention on reaching behaviors in children with spastic CP. The testing procedure consisted of a 2-week baseline, a 4-week intervention, and follow-up at 2 and 4 weeks. Each child received 2 or 3 sessions of the VR intervention for a total of 2 hours of treatment per week. The weekly treatment frequency was discussed and arranged with the parents to increase their child's participation. All participants were required to maintain the frequency and duration of their regular therapies (eg, physical therapy, occupational therapy, speech therapy, and acupuncture) throughout the study period (Appendix 1).

Measurements

Two types of measurements were used in this study: reaching kinematics and a standardized fine motor assessment tool.

Reaching kinematics. Mail-delivery activities in 3 directions (neutral, outward 45°, and inward 45°) were used to examine the reaching performance of all participants. Kinematic measurements were obtained 3 times at baseline (B1, B2, and B3, measured on days 1, 7, and 14, respectively), 4 times during the intervention phase (I1, I2, I3, and I4, measured at the end of each intervention week), and 2 times at follow-up (F1 and F2, measured at the end of follow-up weeks 2 and 4, respectively). Reaching movements were recorded with sampling at 60 Hz by use of 6 cameras (model 370 Vicon Motion Analysis System*) that surrounded the participant: 2 at the front, 2 at the side, and 2 at the back. Each camera was placed approximately 2.5 m from the center of the testing area. The cameras were calibrated prior to each data collection session; the average error was less than 1.4 mm. Two additional video cameras (Sony-DV27†) were placed 45 degrees from the horizontal plane of the child on both sides to record the behaviors.

All participants were tested in the laboratory at the Institute and Faculty of Physical Therapy, National Yang-Ming University, Taipei, Taiwan. All participants were seated in an adjustable special high chair (Tripp Trapp Chair‡) with a testing table in front of them at waist height. A trunk strap surrounded their waists to offer sufficient trunk support. Small reflective markers (9 mm in diameter) were attached to the skin of the shoulder and wrist of the training hand with hypoallergenic double-stick collars.§ One more reflective marker was attached to the opening of the target mailbox.

All participants were videotaped for the entire testing session. Thirty seconds of kinematic data were collected in each trial. Data were collected for a minimum of 6 reaches for each direction. It usually took less than 10 minutes to complete these mail-delivery activities. Children were allowed to rest if necessary.

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* Oxford Metrics Ltd, 14 Minns Estate, West Way, Oxford, Oxfordshire OX2 0JB, United Kingdom.

† Sony, 5F, No. 45, Shihfu Rd, Sinyi District, Taipei City 110, Taiwan.

‡ Stokee, Equipment Shop, PO Box 33, Bedford, MA 01730.

§ Med Associates Inc, PO Box 319, St Albans, VT 05478.

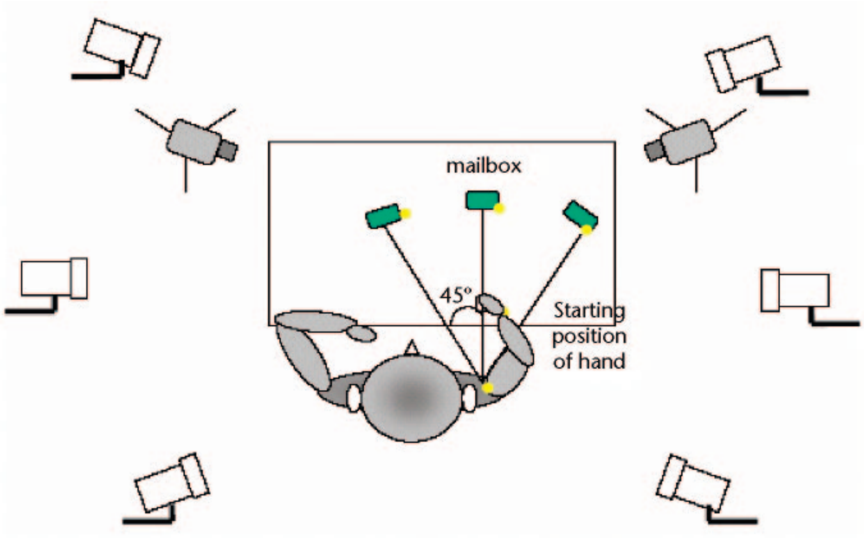

Figure 1.
Experimental setup for testing of reaching kinematics.

Three directions of mail-delivery activities were tested (Fig. 1). The child's training hand was placed at the starting position, which was located about 15 cm forward along the testing shoulder line. The target mailbox (radius=5 cm, height=15 cm) was located one full arm's length forward (neutral direction), 45 degrees outward of shoulder horizontal abduction (outward direction), and 45 degrees inward of shoulder horizontal adduction (inward direction). The child's hand held one 3.5- × 2.5-cm envelope and inserted this envelope into the mailbox at each of 3 locations. All participants were instructed to move as quickly and accurately as possible to complete these tasks. The testing sequence always started from the neutral direction, followed by the outward direction and then the inward direction. Practice was allowed 3 times for each direction before kinematic data were collected.

Raw data were digitized and processed in 3-dimensional position coordinates with Vicon software (version 1.1).* All kinematic data were viewed on videotapes and with the Vicon display program by one of the investigators (LJK) to determine the beginning and end frames of a reach. A reach began at the first frame of the hand leaving the starting position and ended at the first frame of inserting the envelope into the mailbox. The intrarater reliability was .99, as determined by use of the intraclass correlation coefficient method (ICC[3,1]) with 10 randomly selected reaches from 2 children, with coding over a 7-day interval.[19] Reaches were discarded if missing data accounted for more than 20% of a reach, if the missing data could not be interpolated appropriately, as determined by the investigators after careful inspection (eg, missing data at beginning and end frames), or if the participants did not follow instructions. These criteria for missing data were consistent with our previous work and the work of others (eg, Fetters and Kluzik[8] and Chen et al[20]). When necessary, data were interpolated by use of a second-order polynomial method. All data were filtered with a fifth-order Butterworth filter with a cutoff frequency of 6 Hz, and all kinematic measures were computed with MATLAB.‖ Four kinematic parameters of reaching movements were measured: movement time (MT), path length (PATH), peak velocity (PV), and movement units (MUs).

The MT was defined as the time between the beginning and the end frame of a reach.

Hand PATH was a measure of the distance traveled by the hand from the beginning to the end frame of a reach. With a fixed starting position, PATH reflected the straightness of the reaching trajectory.

The amplitude of the resultant PV of the hand was an indirect measure of the amount of force in a reach. The PV was the maximum resultant velocity of the wrist from the beginning to the end frame of a reach.

The number of MUs was a measure of movement smoothness: the fewer the MUs, the smoother the movement. The MU was defined from the acceleration-deceleration profile of the wrist marker by use of a method described in the literature on reaching.[21,22]

From the literature on reaching in normal infants and children, MT, PATH, and MUs are expected to decrease with age and practice, whereas PV is expected to increase with age and practice.[21–25]

Standardized fine motor assessment tool. To measure improvements in UE function, all participants were evaluated once at baseline (B1, the first visit at baseline), at intervention (I4, the end of the fourth intervention week), and at follow-up (F2, the end of the fourth follow-up week) with the Fine Motor Domain of the Peabody Developmental Motor Scales–Second Edition (PDMS-

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‖ The Mathworks Inc, 3 Apple Hill Dr, Natick, MA 01760-2098.

2).[26] Two subtests were included in the Fine Motor Domain: grasping and visual-motor integration. The internal consistency and the interrater reliability of the Fine Motor Domain were reported to be .96 and .98, respectively.[26] The criterion-prediction validity was reported to be .91.[26] The minimal detectable change of the Fine Motor Domain with a 90% confidence level was 4.935, as interpreted from the data reported by Wang et al[27] and by Haley and Fragala-Pinkham.[28] These assessments were conducted by one of the investigators (LJK). The intrarater reliability values for this investigator were .98 (ICC[3,1]) for grasping and .99 (ICC[3,1]) for visual-motor integration. The interrater reliability values between this investigator and a senior pediatric physical therapist (with work experience of more than 7 years) were .87 (ICC[2,1]) for grasping and .88 (ICC[2,1]) for visual-motor integration.

VR Interventions

All participants received individualized VR interventions with 2 VR systems for 2 hours per week over 4 weeks. The 2-hour weekly intervention was distributed into 3 visits, except for 1 child (participant 4, with 2 sessions per week, because of the parents' busy schedule). Children were seated on the special Tripp Trapp Chair with sufficient trunk support during the intervention. Virtual reality programs were selected on the basis of the children's motor abilities, cognition, motivation, and improvement. The training objective was to improve the qualities of participants' reaching behaviors: to move in a faster, smoother, and straighter manner. During the intervention, proper manual guidance or assistance was provided if necessary to help children understand the activities that they performed in the virtual environment. Generally, the 2-hour intervention time during each intervention week was divided into 45 minutes for the VR-based hand rehabilitation training system and 75 minutes for the commercial VR system. Individualized training programs and treatment goals are summarized in Appendix 2.

VR-based hand rehabilitation training system. The VR-based hand rehabilitation training system consisted of a personal computer,[#] a tracker,[**] a sensor glove (5 Digital Data Glove[††]), a liquid crystal display monitor,[‡‡] and a 3-dimensional virtual environment with a corresponding hand displayed on the screen. This VR system could offer both auditory feedback and visual feedback to the children. When the hand was close to the grasping target, the color of the displayed hand changed from gray to yellow. When the target was within the grasping range, the displayed hand on the screen would change to red. When the displayed hand hit the virtual solid objects, a banging sound would commence. The detailed system configuration is reported elsewhere.[29] Three activities (butterfly, peg-board, and pick-and-place blocks) with adjustable difficulties were included in this system with virtual reality modeling language software. All activities were designed to train reaching and grasping of a moving object (butterfly) or stationary objects in different directions (peg-board and pick-and-place blocks). For example, in the butterfly game, a flying butterfly was presented with a choice of different flying routes (straight line, zigzag, spiral, and random) and a choice of different speeds (slow, medium, and fast). The diameter of the objects and the required finger flexion angles for grasping or catching the objects could also be adjusted to create various degrees of difficulty of the activities.

EyeToy-Play system. The commercial EyeToy-Play[§§] VR system consisted of a camera, an ~53-cm (21-in) television, EyeToy-Play software, and PlayStation 2. In this system, the camera was used as a capturing and tracking device to place the children within the computerized VR environment so that they could interact with virtual objects or events. Twelve games are included in EyeToy-Play software, and 8 of them were chosen as the treatment programs (Bubbles, Seaworld, Wishi-Washi, Rocket Rumble, UFO Juggler, Slap Stream, KungFoo, and Boxing Chump. Children were encouraged to reach, as quickly as possible, toward the virtual objects (eg, rats, animated enemies, fish) that appeared in any direction of the television screen in all games. The criteria for choosing the games included whether the games could allow children to perform goal-directed reaching in all directions, to practice anticipatory reaching movements with moving targets, and to experience sufficient satisfaction with easy achievement. A choice of 3 speeds for the moving targets (slow, medium, and fast) allowed the degrees of difficulty of the activities to be changed.

We describe the software game Slap Stream to provide some details regarding what was typically expected from a child in most games. The child could see himself or herself displayed in the middle of the screen. When the child moved his or her arm, the corresponding image inside the television also moved the arm. There were 4 clouds located at the 4 corners of the screen. The task was to smack the gassy rats that appeared randomly in any of the 4 clouds while avoiding the bunny girls. By

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[#] Acer Computer, 8F, No. 88, Sec. 1, Sintai 5th Rd, Sijhih City, Taipei County 221, Taiwan.

[**] Polhemus Co, 40 Hercules Dr, PO Box 560, Colchester, VT 05446.

[††] iReality.com Inc, 1670 S Amphlett Blvd, San Mateo, CA 94402.

[‡‡] Chi Mei Co, No. 59-1, Sanjia Village, Rende Township, Tainan County 717, Taiwan.

[§§] Sony Computer Entertainment America, PO Box 5888, San Mateo, CA 94402.

playing this game, the child was expected to practice reaching in directions that combined either shoulder abduction and flexion or shoulder abduction and extension.

Data Analysis

The kinematics of the mean of the reaches per assessment session were plotted on graphs for each child. The autocorrelation coefficient was computed for each of the reaching kinematics across the baseline and the intervention to examine the serial dependency of reaching data.[30,31] If the data did not show serial dependency, then the 2-standard-deviation–band method was used because the baseline includes a limited number of data points and has a wide variability. Otherwise, if the data showed significant serial dependency and a linear trend, then the data were detrended before the 2-standard-deviation–band method was used for the residuals of the detrended data.[30,31] If the data showed significant serial dependency and a nonlinear trend, the data would not be detrended, and a 2-standard-deviation–band method would not be run. When the 2-standard-deviation–band method was used, 2 horizontal lines located 2 standard deviations above and below the mean data for the phase were drawn across the graphed baseline and intervention. Statistical significance was determined when 2 successive data points occurred outside the 2-standard-deviation band.[30,31] For kinematic variables that reached statistical significance during the intervention, if the values for those kinematic variables during follow-up were still outside the 2-standard-deviation band of the baseline, then the change was defined as being maintained at follow-up.

The PDMS-2 score was reported as a raw score. We used the minimal detectable change reported by Wang et al[27] to determine whether the change in the raw score of the Fine Motor Domain of PDMS-2 after the intervention reflected a real meaningful change.

Results

Kinematics of Reaching Behaviors

The total number of reaching behaviors performed in 9 measurement sessions was 813; 576 of them met the extraction criteria and were used to compute kinematic measures. Each child contributed 3 to 7 reaches in each assessment session.

Few reaching kinematics showed serial dependency with significant autocorrelation coefficients. Among them, PATH and MUs for participant 1 in the outward direction and MT and MU for participant 4 in the neutral direction also showed a linear trend. Consequently, these variables were detrended before the 2-standard-deviation–band method was applied.

Figures 2, 3, 4, and 5 illustrate the kinematics of reaching that had statistical significance in 4 children, and Table 2 summarizes the significant changes in kinematics for each child.

Participant 1, a boy, was 6 years 4 months of age and had a diagnosis of spastic quadriplegia. His right hand met our inclusion criteria and was his preferred hand. His cognition was within the normal range, as confirmed from the medical records. Motivation for and cooperation with his regular therapies were fair. At baseline, he showed difficulties in performing reaching in all directions, with slow movements. Consequently, his VR intervention focused on reaching in all directions.

With respect to the baseline, participant 1 exhibited significantly smoother reaches in the neutral direction, significantly straighter and smoother reaches in the outward direction, and significantly faster and smoother reaches in the inward direction during the intervention. During follow-up, participant 1 maintained smoother reaches in the neutral and inward directions.

Participant 2, a girl, was 8 years 6 months of age and had a diagnosis of spastic quadriplegia. Both of her hands met our inclusion criteria, and the right hand (the preferred hand) received VR training. She could perform advanced fine motor skills with her right hand, such as writing and stringing beads. Her cognition was within the normal range, as confirmed from the medical records. Motivation for and cooperation with regular physical therapy were good; however, she became frustrated easily while performing activities that she was not good at performing. At baseline, she showed difficulties in performing reaching in the abduction direction. Therefore, her VR training emphasized activities in the abduction direction.

With respect to the baseline, participant 2 exhibited significantly more forceful reaches in the neutral direction, significantly straighter reaches in the outward direction, and significantly more forceful reaches in the inward direction during the intervention. During follow-up, participant 2 maintained straighter reaches in the outward direction and more forceful reaches in the inward direction.

Participant 3, a boy, was 5 years 3 months of age and had a diagnosis of spastic quadriplegia. Both of his hands met the inclusion criteria, and the right hand (the preferred hand) received VR training. His right hand could not perform advanced hand skills, such as using scissors or fastening buttons. He was diagnosed as having mild mental retardation, as confirmed by the medical records. Motivation for and cooperation with regular physical therapy were poor. The therapist needed to use some positive reinforcement (eg, snacks

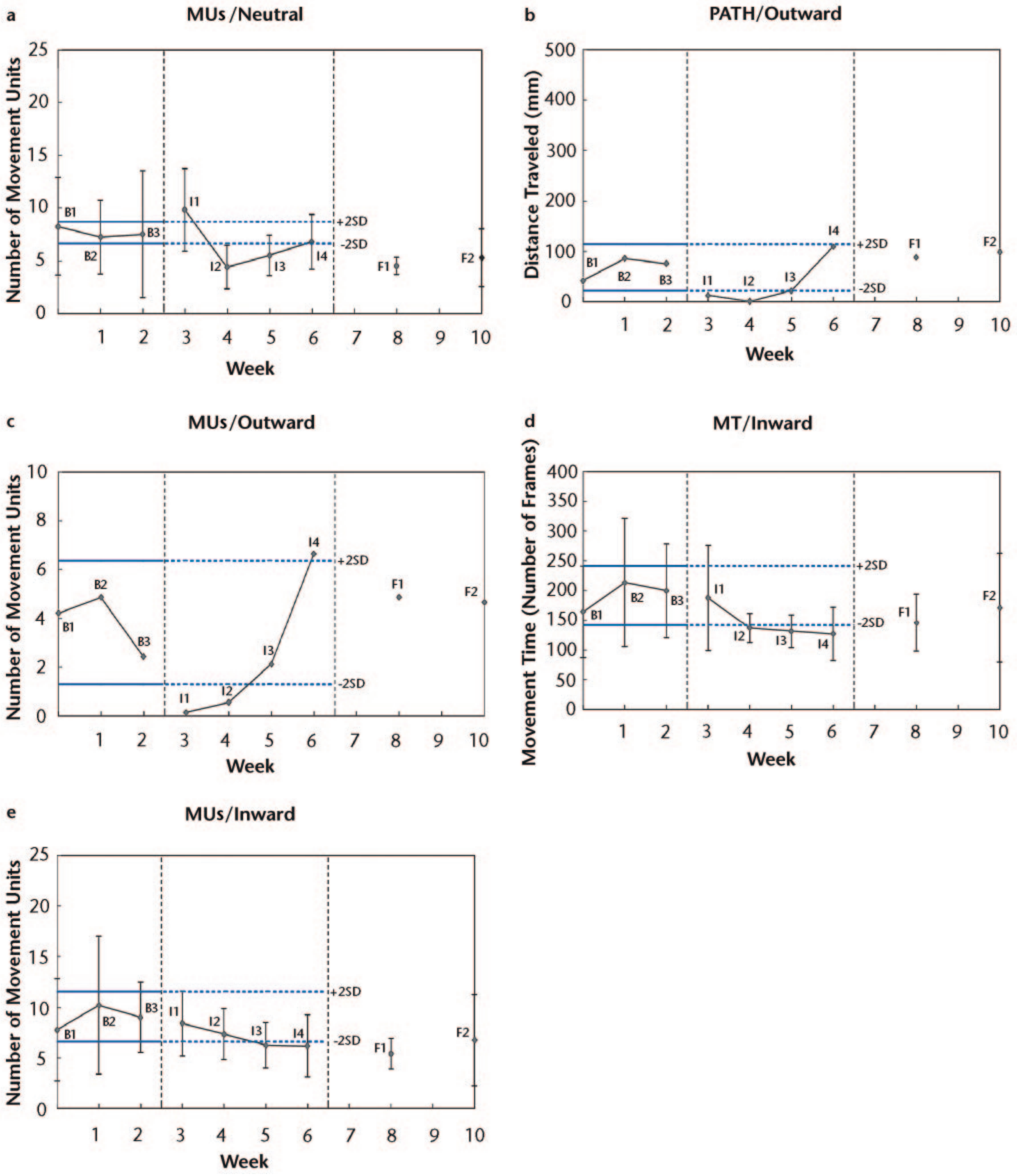

Figure 2.

Reaching kinematics for participant 1 in mail-delivery activities. (a) Movement units (MUs) in the neutral direction. (b) Detrended path length (PATH) in the outward direction. (c) Detrended MUs in the outward direction. (d) Movement time (MT) in the inward direction. (e) MUs in the inward direction. Baseline (B1–B3), intervention (I1–I4), and follow-up (F1 and F2) scores are shown, along with lines marking the 2-standard-deviation (2SD) band (— for baseline and --- for intervention). Error bars show 1 standard deviation of the reaches.

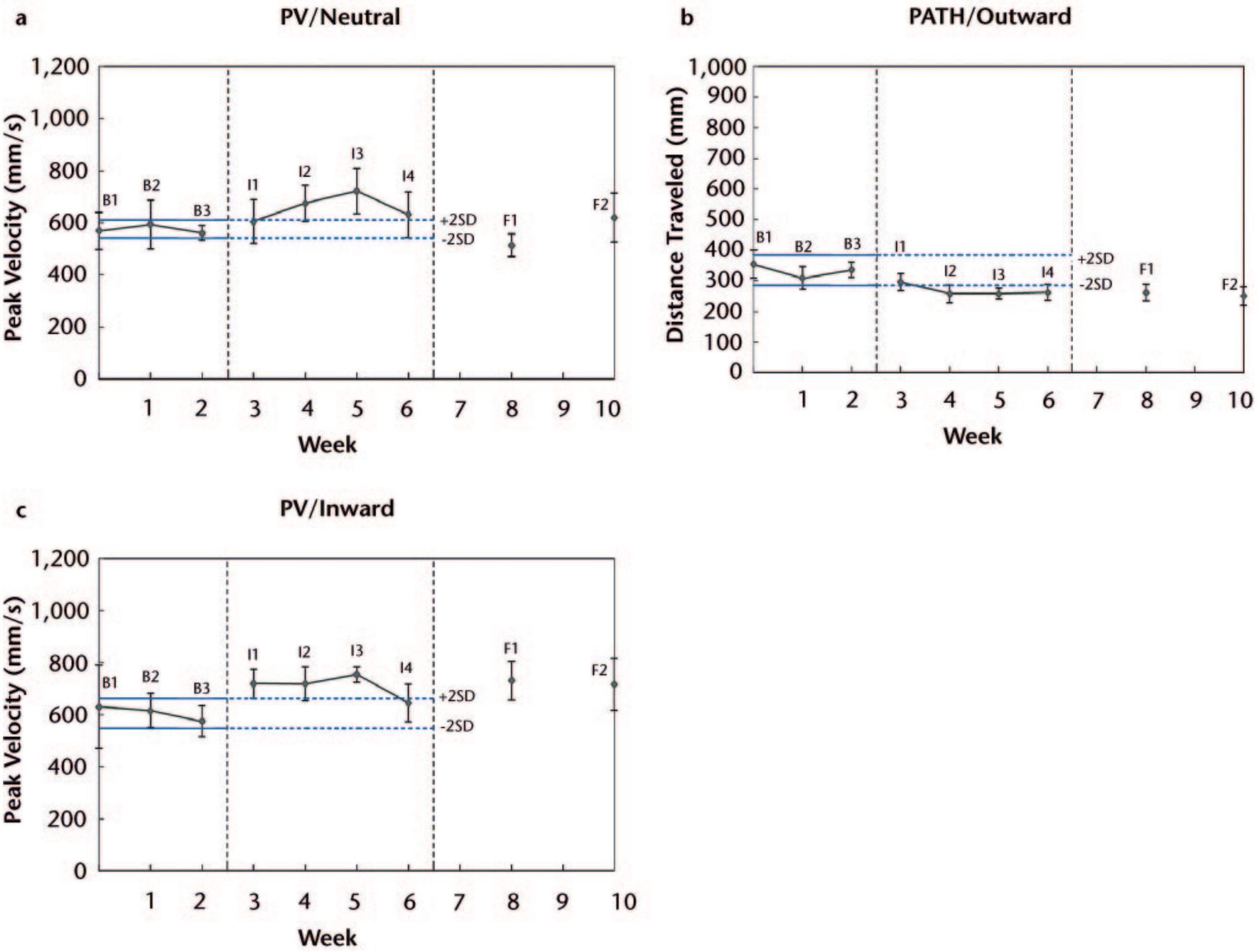

Figure 3.
Reaching kinematics for participant 2 in mail-delivery activities. (a) Peak velocity (PV) in the neutral direction. (b) Path length (PATH) in the outward direction. (c) PV in the inward direction. Baseline (B1–B3), intervention (I1–I4), and follow-up (F1 and F2) scores are shown, along with lines marking the 2-standard-deviation (2SD) band (— for baseline and --- for intervention). Error bars show 1 standard deviation of the reaches.

and juice) to encourage him during regular therapy hours. At baseline, he showed difficulties in performing reaching in all directions. Therefore, his VR training emphasized activities in all directions.

With respect to the baseline, participant 3 exhibited no changes in the neutral direction, significantly less forceful reaches in the outward direction, and significantly more forceful reaches in the inward direction during the intervention. During follow-up, participant 3 maintained only the more forceful reaches in the inward direction.

Participant 4, a boy, was 4 years 8 months of age and had a diagnosis of left spastic hemiplegia. Both of his hands met our inclusion criteria, and the left hand (the affected hand) received VR training. He could perform advanced skills with both hands but preferred using his right hand (nonaffected hand) for most daily activities. Motivation for and cooperation with regular physical therapy were good. At baseline, he showed slight difficulties in performing reaching in all directions with his left hand. Therefore, his VR training emphasized activities in all directions.

With respect to the baseline, participant 4 exhibited significantly faster, straighter, and smoother reaches in the neutral direction, significantly more forceful reaches in the outward direction, and significantly smoother reaches in the inward direction during the intervention. During follow-up, participant 4 main-

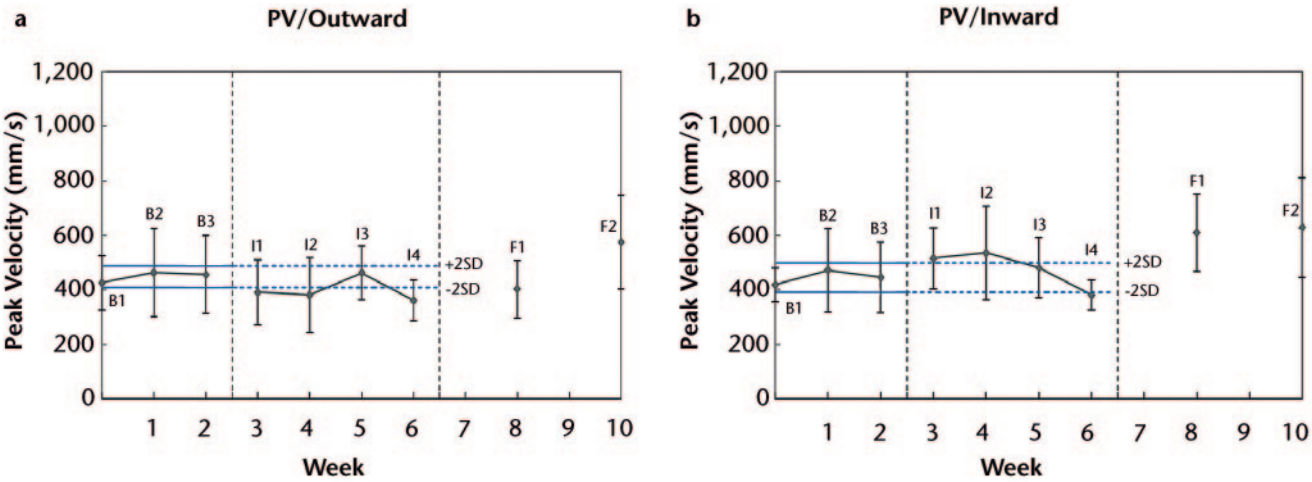

Figure 4.
Reaching kinematics for participant 3 in mail-delivery activities. (a) Peak velocity (PV) in the outward direction. (b) PV in the inward direction. Baseline (B1–B3), intervention (I1–I4), and follow-up (F1 and F2) scores are shown, along with lines marking the 2-standard-deviation (2SD) band (— for baseline and --- for intervention). Error bars show 1 standard deviation of the reaches.

tained smoother reaches in the inward direction.

Summary of Findings

Neutral direction. With respect to the baseline, participant 4 exhibited significantly faster and straighter reaches, participant 2 had significantly more forceful reaches, and participants 1 and 4 had significantly smoother reaches during the intervention. During follow-up, only participant 1 maintained smoother reaches.

Outward direction. With respect to the baseline, participants 1 and 2 exhibited significantly straighter reaches during the intervention. Participant 4 had more forceful reaches and participant 3 had less forceful reaches during the intervention. Participant 1 showed significantly smoother reaches during the intervention. During follow-up, only participant 2 maintained straighter reaches.

Inward direction. With respect to the baseline, participant 1 showed significantly faster reaches during the intervention. Participants 2 and 3 showed significantly more forceful (larger PV) reaches during the intervention. Participants 1 and 4 had significantly smoother reaches during the intervention. During follow-up, participants 2 and 3 maintained more forceful reaches, whereas participants 1 and 4 maintained smoother reaches.

Standardized Fine Motor Assessment Tool

Participant 1 showed an increase of 11 points in the total score on the Fine Motor Domain of the PDMS-2 during the intervention and an increase of 1 point at follow-up. All of the improvement occurred in the visual-motor integration subtest.

Participant 2 showed an increase of 1 point in the total score on the Fine Motor Domain of the PDMS-2 during the intervention but did not show a change at follow-up. This child had the highest score on the visual-motor integration subtest at baseline (ceiling effect); therefore, the improvement occurred in the grasping subtest.

Participant 3 showed an increase of 5 points in the total score on the Fine Motor Domain of the PDMS-2 during the intervention and an increase of 3 points at follow-up. All of the improvement occurred in the visual-motor integration subtest.

Participant 4 showed an increase of 4 points in the total score on the Fine Motor Domain of the PDMS-2 during the intervention but showed a decrease of 1 point at follow-up. The grasping subtest showed an increase of 1 point during the intervention but showed no change at follow-up. The visual-motor integration subtest showed an increase of 3 points during the intervention but showed a decrease of 1 point at follow-up.

From baseline to the intervention, all children showed an increase in the total score on the PDMS-2 (range=1–11 points) (Tab. 3). From the intervention to follow-up, participants 1 and 3 showed an increase in the total score on the PDMS-2 (range=1–3 points), participant 2 showed an unchanged score, and participant 4 showed a decrease of 1 point. Participant 2 had the highest

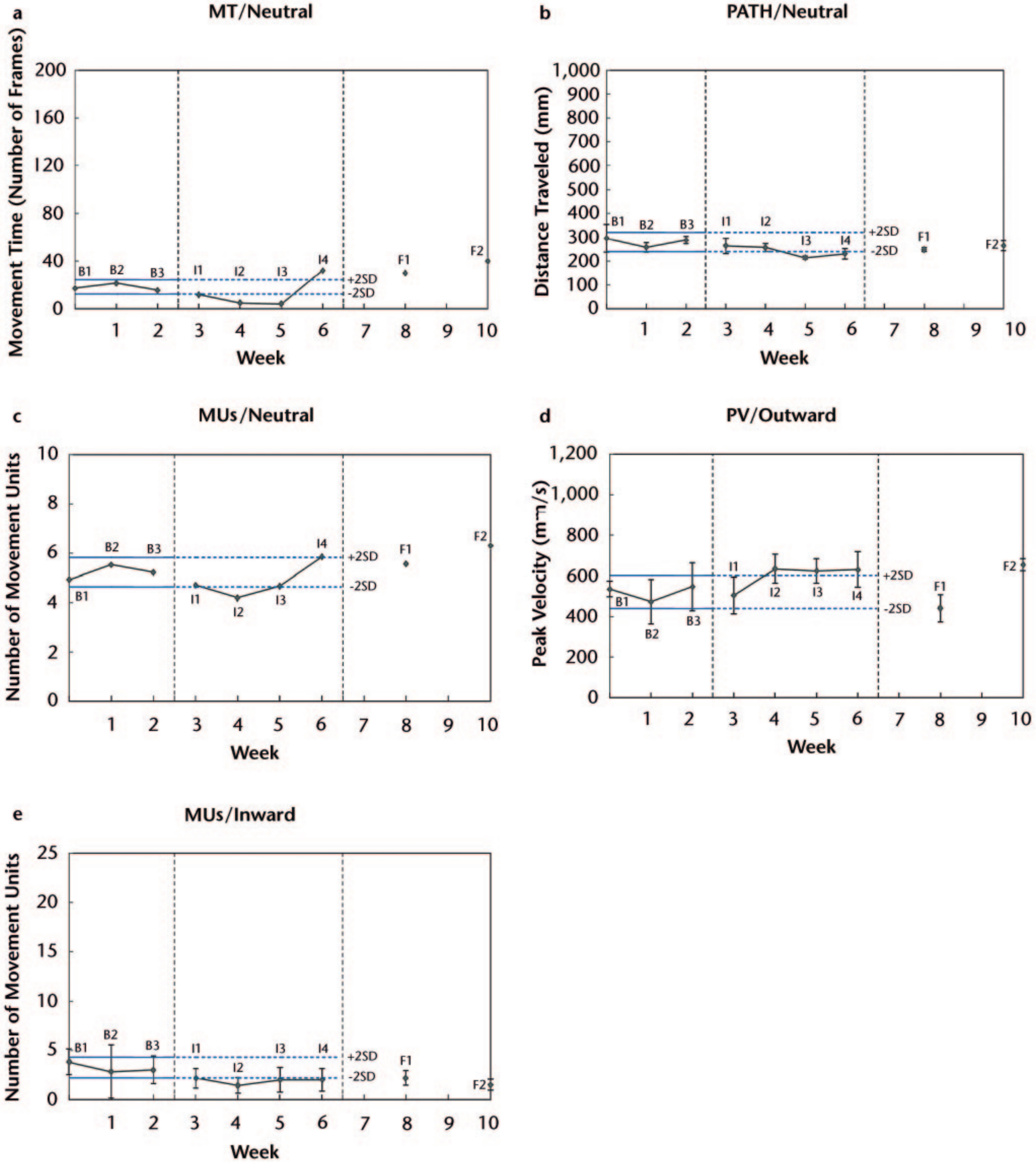

Figure 5.

Reaching kinematics for participant 4 in mail-delivery activities. (a) Detrended movement time (MT) in the neutral direction. (b) Path length (PATH) in the neutral direction. (c) Detrended movement units (MUs) in the neutral direction. (d) Peak velocity (PV) in the outward direction. (e) MUs in the inward direction. Baseline (B1–B3), intervention (I1–I4), and follow-up (F1 and F2) scores are shown, along with lines marking the 2-standard-deviation (2SD) band (— for baseline and --- for intervention). Error bars show 1 standard deviation of the reaches.

Table 2.
Summary of Significant Changes in 4 Children During Intervention and Follow-up[a]

Direction	Variable	Participant 1		Participant 2		Participant 3		Participant 4	
		Intervention	Follow-up	Intervention	Follow-up	Intervention	Follow-up	Intervention	Follow-up
Neutral	MT							↓ from B	
	PATH							↓ from B	
	PV			↑ from B					
	MUs	↓ from B	↔					↓ from B	
Outward	MT								
	PATH	↓ from B		↓ from B	↔				
	PV					↓ from B[b]		↑ from B	
	MUs	↓ from B							
Inward	MT	↓ from B							
	PATH								
	PV			↑ from B	↔	↑ from B	↔		
	MUs	↓ from B	↔					↓ from B	↔

[a] MT=movement time, PATH=path length, PV=peak velocity, MUs=movement units, B=baseline. ↓ indicates that the value decreased, ↑ indicates that the value increased, blank cells indicate no changes, ↔ during follow-up means that the improvement during the intervention was maintained during follow-up.
[b] Different from the expected direction.

score on the PDMS-2 during the intervention, but that situation may have created a ceiling effect for her not to show improvement from the intervention to follow-up.

Discussion

The results of the present study demonstrated that 3 of the 4 children with CP showed some improvement in the quality of reaching performance during the VR intervention, and the training effects were partially maintained 4 weeks after the intervention. Our findings were consistent with the finding of a previous study[16] that VR intervention has positive training effects on reaching performance in children with CP.

The VR systems used in our study allowed the children to practice reaching repeatedly in various directions and contexts; this practice improved the quality of their reaching, as measured with kinematic parameters. For example, children could repeatedly practice about 100 reaches in a 3-minute session with the EyeToy-Play system. Repetition is an important aspect of practice, and repetition of a task has been shown to improve performance in people with or without disabilities.[15] Repetition can be described as repeated attempts to solve a goal-related problem by building on previous attempts, that is, repetition without repetition.[15,32] Repetitive practice

Table 3.
Raw Scores for the Fine Motor Domain of the Peabody Developmental Motor Scales–Second Edition at Each Phase

Participant	Grasping Subtest			Visual-Motor Integration Subtest			Total Score on Fine Motor Domain		
	Baseline	Intervention	Follow-up	Baseline	Intervention	Follow-up	Baseline	Intervention	Follow-up
1	46	46	46	95	106	107	141	152[a]	153
2	48	49	49	144	144	144	192	193	193
3	44	44	44	114	119	122	158	163[a]	166
4	51	52	52	137	140	139	188	192	191

[a] Above the minimal detectable change.

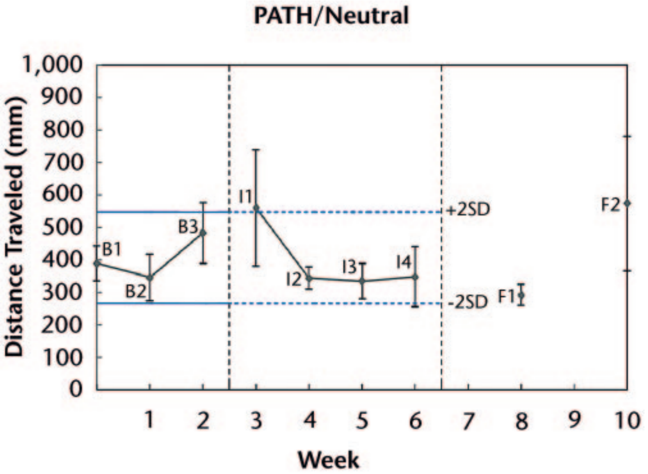

Figure 6.
Path length (PATH) in the neutral direction for participant 3. This child began to improve his reaching path length after the second week of the intervention. Baseline (B1–B3), intervention (I1–I4), and follow-up (F1 and F2) scores are shown, along with lines marking the 2-standard-deviation (2SD) band (— for baseline and --- for intervention). Error bars show 1 standard deviation of the reaches.

enables the system to coordinate the muscular synergies that move the segmental linkage in a desired manner to accomplish the task goal.[32] The children in our study repeated practicing to accomplish the reaching task by coordinating their arms and hands to touch the target and to gradually discover an efficient pattern for their reaching, as featured by moving in a faster, straighter, and smoother manner during the intervention.

The children in the present study showed improvements in different kinematic parameters of reaching performance. This finding was consistent with the propositions by Zanone et al[33] that people may demonstrate unique motor learning strategies and, therefore, that preferred motor solutions depend on the specific characteristics of an individual's "intrinsic dynamics" (ie, organismic constraints) and how these intrinsic constraints interact with the information available in the environment. For example, participant 1 showed improvement in reaching with a smoother pattern, whereas participant 2 exhibited improvement in reaching performance by producing more force.

The VR systems used in our study could display augmented visual and auditory information during performance. This kind of "augmented information" may assist in children's searching strategies to find the "solution" to performing a task.[32] That is, children may perceive the visual information provided by the displayed hand on the screen and use this information for their later actions to gradually search for efficient reaching patterns. Moreover, the VR systems used in our study allowed the task difficulties of the games to be adjusted according to an individual child's motor abilities and gradually offered to children with CP step-by-step guidance for achieving efficient reaching patterns.

Participants 2 and 3 did not benefit from the VR intervention as much as the others in terms of improving their reaching patterns in our study. Participant 2 was the oldest participant in our study (8 years 6 months old) and was the only one who received the direction-specific VR training program (focusing only on the outward direction). Consequently, her reaching pattern in the outward direction changed to a straighter pattern during the intervention phase, and this change was maintained at follow-up. The inward direction and neutral direction also showed improvements in the form of increasing forcefulness in her reaches during the intervention, and these improvements were partially maintained at follow-up. According to the narrative reports from her parents, her performance in using the training hand in the abduction direction in daily life and regular therapy sessions improved a great deal after the second week of the VR intervention. However, our sensitive kinematic measures did not reflect the changes reported by the parents. One possible reason for this difference is that the time for evaluating her during the intervention was interfered with by her busy school schedule. She came to our evaluation directly after whole-day school activities. She always showed fatigue when arriving at our evaluation session. Alternatively, the difference may have been attributable to our direction-specific intervention.

Participant 3 showed very limited improvements in his reaching. He was the only participant who had mildly retarded mental development. The first 2 weeks of the VR intervention for this participant were mainly used to establish the causality between his action and the corresponding hand in the virtual world. He started to show some improvements in reaching after the third week of the intervention, but this result did not meet the criterion for significance determined by the 2-standard-deviation–band method (Fig. 6). Therefore, for treating children with mild mental retardation, a "pretraining" period may be necessary to establish the relationship between their actions and the corresponding images inside the computer, or the intervention phase may need to be lengthened to observe improvements.

Most of the children exhibited increases in their scores on the Fine Motor Domain of the PDMS-2 during the intervention, but the change scores for participant 1 and participant 3 only were above the minimal detectable change (ie, 5 points). Participant 2 reached the ceiling effect on the Fine Motor Domain of the PDMS-2 during baseline. This assessment tool might not have detected her real improvement because of the ceiling effect. The scores for participant 4 increased 4 points during the intervention; this value approached the minimal detectable change.

Improvements on the PDMS-2 for 3 of the 4 children occurred in the visual-motor integration subtest. The items included in this subtest were activities related to eye-hand coordination and were the training programs used in the VR intervention. For example, when the EyeToy-Play programs were used to train the children, the children were instructed to hit the suddenly appearing target (ie, cartoon characters). Children had to perceive the appearance of the target in various locations of the screen and then move their arms to quickly reach toward the target. By repeatedly practicing these activities, children improved their performance in eye-hand coordination; this improvement was reflected in the scores on the visual-motor integration subtest.

In the present study, we used 2 different VR systems for training. We did not plan to compare the laboratory-built VR system with the commercial VR system in the present study. These 2 systems offered different types of training for children with CP. The laboratory-built VR system offered more flexibility in adjusting task difficulties, such as the required flexion angle of grasping or the flying route of the target. However, a lack of sufficient animation and difficulty in programming language were the flaws of this system. In contrast, the commercial VR system, with attractive animated characters, could offer more fun during training for children with CP. However, a lack of sufficient control of task difficulties was the main flaw of this system. Although the commercial system offered 3 different speeds, the medium and fast speeds were too fast for most of the children with CP. A professional therapist had to select programs suitable for children with CP.

The present study had several limitations. We observed some practice effects between measurement points B1 and B2, even though the children were familiar with the motion analysis system and the laboratory. We observed only 3 points during baseline for practical reasons (parents' requests and ethics issues). Further study might increase the number of observations to show the trend during baseline. The primary scorer for the children's PDMS-2 was not masked with regard to their treatment status, although a secondary scorer, who was unaware of the children's status, coded some of the data and showed reliable scoring. The investigator who viewed the kinematic data was not masked, either. Further study might include an independent scorer who is unaware of the children's treatment status to avoid possible experimenter bias. We did not measure the participation level of the children with CP in the present study. Nevertheless, the findings from the present study may serve as the scientific basis for designing a larger-scale clinical randomized controlled trial to examine the effectiveness of a VR intervention for enhancing the UE function of children with CP.

Conclusion

A 4-week VR training program demonstrated the potential to improve reaching performance and control in children with CP, especially those who had normal cognitive development and showed good cooperation.

Dr Chen and Dr Sung provided concept/idea/research design. Dr Chen provided writing. Dr Chen and Ms Kang provided data collection and analysis. Dr Doong provided project management. Dr Chuang and Dr Lee provided facilities/equipment. Dr Sung provided institutional liaisons. Dr Lee, Dr Tsai, and Dr Jeng provided consultation (including review of manuscript before submission).

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Appendix 1.

Concurrent Therapies During the Study Period

Participant	Therapy	Frequency/Duration	Content
1	Physical	2 sessions/wk 30 min/session	Walking training (with walker), treadmill exercise, and upper-limb exercise (eg, push balls)
	Occupational	2 sessions/wk 30 min/session	Fine motor activities (eg, peg-board activity, pick up balls)
2	Physical	1 session/wk 30 min/session	Upper-limb weight-bearing exercise (eg, moving prone scooter by pushing hands), treadmill exercise, push-ups
	Occupational	1 session/wk 30 min/session	Fine motor skills (eg, using chopsticks, drawing lines)
3	Physical	2 sessions/wk 30 min/session	Walking training (with walker or forearm crutches), treadmill exercise
	Occupational	2 sessions/wk 30 min/session	Visual-motor integration activities (eg, peg-board activity, matching shapes, pasting stickers)
4	Physical	1 session/wk 30 min/session	Advanced balance training (eg, hopping on left leg, throwing balls when standing on unstable surfaces)
	Occupational	1 session/wk 30 min/session	Fine motor skills (eg, using chopsticks, hitting moving balls)

Appendix 2.
Individualized Treatment Program[a]

Participant	Category	Wk 1	Wk 2	Wk 3	Wk 4
1	Goals	1. Familiarize with 2 training systems 2. Encourage wider range of reaching to all directions with well-supported trunk	1. Increase range of reaching with decreased trunk support 2. Encourage quick and accurate reaching movement	Require better achievement (eg, quicker and more accurate) in every task with decreased trunk support	Require better achievement in every task with decreased trunk support and trunk weight shifting
	Main training programs	All 3 activities of VR systems with easily achieved settings; 3 EyeToy-Play system programs (Bubbles, Seaworld, and Wishi-Washi) with wide-range reaching and no speed requirement	All 3 activities of VR systems with increased difficulties; 2 EyeToy-Play system programs (easiest level of Rocket Rumble and Slap Stream) with slight speed and accuracy requirements	All 3 activities of VR systems with increased difficulties; 2 EyeToy-Play system programs (easiest level of Slap Stream and KungFoo) with speed and accuracy requirements	All 3 activities of VR systems with challenging settings; 2 EyeToy-Play system programs (easiest level of KungFoo and Boxing Chump) with speed and accuracy requirements and more repetitions
2	Goals	1. Familiarize with 2 training systems 2. Encourage quick and accurate reaching movement with well-supported trunk	1. Train fast, accurate, and lasting reaching movement with decreased trunk support 2. Require better achievement in every task	1. Keep increasing speed and accuracy in reaching with trunk weight shifting; more repetition to abduction 2. Require better achievement in every task	1. Require high achievement in training tasks without trunk support 2. Train variety and efficiency of reaching (with emphasis on abduction) and grasping movements
	Main training programs	All 3 activities of VR systems with easily achieved settings; 3 EyeToy-Play system programs (easiest level of Rocket Rumble, Slap Stream, and KungFoo) with slight speed and accuracy requirements	All 3 activities of VR systems with increased difficulties; 2 EyeToy-Play system programs (easiest level of Slap Stream and KungFoo) with speed and accuracy requirements; 1 program (easiest level of UFO Juggler) with sustained holding ability requirement	All 3 activities of VR systems with increased difficulties; 2 EyeToy-Play system programs (easiest level of Slap Stream and KungFoo) with speed and accuracy requirements; 1 program (easiest level of UFO Juggler) with sustained holding ability requirement	All 3 activities of VR systems with highest degrees of difficulty; 2 EyeToy-Play system programs (easiest level of Slap Stream and KungFoo) with speed and accuracy requirements; 1 program (easiest level of UFO Juggler) with sustained holding ability requirement; 1 program (Boxing Chump) for training repeated abduction reaching

(Continued)

Appendix 2.
Continued

Participant	Category	Wk 1	Wk 2	Wk 3	Wk 4
3	Goals	1. Familiarize with 2 training systems 2. Encourage wider range of reaching to all directions with well-supported trunk 3. Promote cooperation for treatment	1. Encourage mastery of training systems as well as active participation in treatment 2. Encourage wider range of reaching and increasing speed with well-supported trunk	1. Increase range and speed of reaching with slightly decreased trunk support 2. Encourage more successful trials in reaching and grasping tasks	Require better achievement in reaching and grasping tasks with decreased trunk support
	Main training programs	All 3 activities of VR systems with easily achieved settings; 3 EyeToy-Play system programs (Bubbles, Seaworld, and Wishi-Washi) for training wide-range reaching	All 3 activities of VR systems with increased difficulties; 2 EyeToy-Play system programs (Bubbles and Wishi-Washi) for training wide-range reaching; 1 program (easiest level of Slap Stream) with speed and accuracy requirements	All 3 activities of VR systems with increased difficulties; 2 EyeToy-Play system programs (easiest level of Rocket Rumble and Slap Stream) with speed and accuracy requirements	All 3 activities of VR systems with increased difficulties; 2 EyeToy-Play system programs (moderate level of Rocket Rumble and easiest level of KungFoo) with speed and accuracy requirements
4	Goals	1. Familiarize with 2 training systems 2. Encourage more frequent use of affected side to perform quick and accurate reaching	1. Require quick and accurate reaching and grasping movements of affected hand 2. Require better achievement in every task	1. Require quick and accurate reaching and grasping movements of affected hand 2. Require better achievement in challenging tasks	1. Require high achievement in challenging tasks 2. Train high variety and efficiency of reaching movements
	Main training programs	All 3 activities of VR systems with easily achieved settings; 3 EyeToy-Play system programs (easiest level of Rocket Rumble, Slap Stream, and KungFoo) with slight speed and accuracy requirements; 1 program (Boxing Chump) required more intensively repeated reaching with affected hand	All 3 activities of VR systems with increased difficulties; 3 EyeToy-Play system programs (easiest level of Slap Stream and KungFoo and moderate level of Rocket Rumble) with speed and accuracy requirements; 1 program (moderate level of Boxing Chump) for training intensive use of affected hand	All 3 activities of VR systems with increased difficulties; 3 EyeToy-Play system programs (easiest level of KungFoo, moderate level of UFO Juggler, and hardest level of Rocket Rumble) with speed, accuracy, and sustained holding ability requirements	All 3 activities of VR systems with highest degrees of difficulty; 3 EyeToy-Play system programs (easiest level of Slap Stream and moderate level of KungFoo and UFO Juggler) with speed, accuracy, and sustained holding ability requirements; 1 program (moderate level of Boxing Chump) for training intensive use of affected hand

[a] VR=virtual reality.