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Case Report

Embodied Virtual Reality Mirror Visual Feedback for an Adult with Cerebral Palsy

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Abstract: Virtual reality-assisted physical therapy and mirror visual feedback (MVF) are promising treatments for children with cerebral palsy (CP). However, thus far, neither interventions' use has been reported in adults with CP. The following case report examines the safety and feasibility of using customized virtual reality (VR) interventions to deliver MVF to an adult with hemiplegic CP and right sided pain, weakness, and dystonias. A weekly intervention was delivered in an ambulatory care setting over one year. Self-reported pain, motor function, anxiety, disability, quality of life and depression were monitored weekly. The treatment was acceptable and well tolerated with no instances of cybersickness. The intervention showed immediate and consistent pain relief during treatment, similar to those reported in other studies, with the percentage of pain relief during sessions ranging from 6.25% to 38.5%. Motor function, including range of motion, control, and dexterity, were improved per patient report. However, the duration of pain relief lasted only 2–4 days between sessions. The authors believe that the present findings may inspire others treating adults and children with CP to explore the use of MVF and VR to enhance rehabilitation with an emphasis on adapting technologies for home use. Further implications of these findings for the future are discussed.

Keywords: Virtual Reality, Case Reports, Physical Therapy Modalities, Cerebral Palsy, Mirror Visual Feedback

1. Introduction

Cerebral palsy (CP) is a diverse condition categorized by permanent central motor problems caused by a variety of factors during fetal development. CP primarily affects muscle tone, posture, and movement. The prevalence of CP is approximately 2 per 1,000 live births, and the highest risk is noted in preterm and low-birthweight infants [1]. The levels of severity and disability range widely, and may involve additional symptoms (i.e., altered sensation, seizures, chronic

and pain), as well as musculoskeletal, intellectual, communication, and behavioral disabilities. Although the causes of CP are multifactorial and perinatal in nature, the manifestation of symptoms may change over the lifetime of a patient as the brain matures. Thus, interventions that are effective for children merit consideration in adults.

Most treatments for CP focus on children, and multidisciplinary teams collaborate with families to maximize functioning and independence. The most intensively targeted symptoms are spasticity and hyperreflexia that lead to contractures that limit functioning. Botulinum toxin has

exhibited the strongest efficacy versus other oral drug treatments. Although physical and occupational therapies are established standards of care, their effectiveness is uncertain. However, these therapies appear to be important for caretakers in facilitating and maximizing patient independence.

Nearly all children with paralysis on only one side (hemiplegia) will eventually walk. However, young adults report low quality of life, as well as poor social and peer support. Poor quality of life is also correlated with higher levels of pain [2]. Therefore, novel treatments, especially targeting pain behaviors and improvement of the current therapeutic options for adults are warranted. Several promising trials investigating children with CP have included Mirror Visual Feedback (MVF) [3-5] and virtual reality (VR)-mediated physical and occupational therapy [6] in their approach.

MVF – occasionally termed Mirror Box Therapy – was originally developed by VS Ramachandran for the relief of phantom limb pain (PLP) and sensations in amputees [7]. It involves reflecting one's "good" hand/foot/limb in a mirror to create a visual illusion for the patient that the missing body part is present and moving. Successful improvement of phantom limb sensations has been documented using this intervention. MVF has been applied to other unilateral motor and sensory symptoms with promising outcomes in complex regional pain syndrome type I (CRPS), post-stroke weakness, post-surgical recovery, multiple sclerosis, and rheumatoid arthritis.

The mechanism of MVF treatment is believed to be based on the interaction between the visual, motor, and tactile systems in various regions of the brain. Neuroimaging studies suggest MVF increases excitability of the ipsilateral primary motor cortex that projects to affected body parts leading to increased action control. More recent systematic reviews suggest MVF facilitates neural activities in diverse regions of the brain [8]. Pain specialists often note that increased movement often precedes pain relief. The perception of visual movement may be used to modulate sensation and movement by implicit behavioral learning/conditioning in MVF. Interestingly, a neuroimaging study performed by Diers *et al.* found evidence that virtually delivered MVF (VR-MVF) may be superior to the classical mirror box. In their study, immersive VR-MVF delivered to healthy subjects achieved greater activation in the primary sensorimotor cortex than traditionally mediated mirror therapy [9].

To date, there are no reported uses of MVF delivered adults with CP. A handful of trials investigating MVF in children with CP have been conducted, along with a systematic review [3-5]. The review concluded that MVF improves muscle strength, motor speed, accuracy, and muscle activity in both hands of children with CP. In 2019, a controlled trial of 30 children showed that MVF delivered over 6 weeks was useful in improving dexterity but not grasp in CP [4]. In a recent randomized controlled trial (N=30), MVF combined with power and strength exercises was found to improve function and performance of the affected upper extremities of participants with spastic CP [5].

While more than 23 randomized controlled trials of fair-to-good methodological quality have investigated the use of VR for children with CP, no reports of its use in adults were found. These studies have been summarized in a systematic review [6], which concluded that VR may demonstrate short-term benefits to limb function, postural control, and balance in pediatric CP. Investigators hypothesize that the possible mechanisms for VR effects may include increases in cognitive engagement paired with a motor task, the ability to increase external cues, and a dosage effect mediated by increased motivation and repetitions from gamified designs. However, there is controversy as to whether these gains are translatable and transferable from the virtual to the natural environment [10].

Although the integration of VR and MVF has been reported for other conditions, to our knowledge the combination of VR and MVF for CP has not been investigated or reported in the literature. In 2007, Murry and colleagues [11] reported the use of fully embodied immersive VR-MVF for the treatment of PLP for the first time. In 2014, Ortiz-Catalan and colleagues [12] reported a PLP case that was unresponsive to traditionally delivered MVF that improved with augmented reality-delivered MVF. Similar positive results have also been reported in larger studies of PLP using simple and immersive VR delivery systems [13, 14]. VR-MVF studies reported an average pain reduction of 38–40% in patients with upper-limb amputation. Moreover, there are two reports of successfully delivered VR-MVF in CRPS (another chronic pain condition). The first, published in 2010, was an open-label case series using non-immersive VR [15]. The second, published in 2015, was a case report of immersive VR developed for pediatric patients with CRPS [16]. In a 2018 review of technology assisted forms of MVF, Darbois *et al.* [17] identified over 49 reports of VR-MVF applications. Since that time, a handful of controlled trials have emerged [18-22] supporting the efficacy of VR-MVF in various unilateral motor and sensory illnesses.

Given the mounting evidence supporting the use of VR and MVF for pediatric CP patients and the paucity of treatment studies for adults with CP, we report on the use of VR-MVF in a single case of an adult with CP during the course of care in an outpatient setting. We describe the preliminary findings of this treatment using a low-cost, commercially available, fully embodied immersive VR system over a period of one year. We examined the potential acceptability and feasibility of this approach to determine if further investigation or clinical trials of VR-MVF for adults with CP is warranted.

Written informed consent was provided by the patient in accordance with Stanford University School of Medicine and Healthcare Hospital and Clinics (Stanford, CA, USA).

2. Case Report

The patient was a late, middle-aged female with a history of secondary dystonia and hemiplegia due to CP treated for over 15 years with injections of botulinum toxin. A decade prior to presentation, the patient underwent unilateral implantation of a (left) subthalamic nucleus and globus

pallidus interna Deep Brain Stimulator (DBS), resulting in improvement of the proximal arm and leg dystonia. She had lifelong pain in her right arm and shoulder and received occupational therapy in pain clinics. She had not previously received a course of MVF.

2.1. Past Medical History

The patient developed CP due to RH-factor incompatibility and suffered from chronic athetoid movements throughout her life. She had received treatment for a seizure disorder with phenobarbital through the age of 12, and since that time was seizure-free. The patient was characterized by right sided dystonia, carpal tunnel syndrome, frozen shoulder, and elbow tendinitis arthritis.

The patient suffered a traumatic brain injury (TBI) caused by a wheelchair fall in her 30's, with imaging revealing the presence of osteomalacia and mild closed head injury. She reportedly lost consciousness for approximately 30 seconds, and experienced post-traumatic amnesia for 48 hours. As a result of the accident, the patient lost both olfactory and gustatory sensations. Other symptoms included cognitive decline, fatigability, sensitivity to noise, chronic visual hallucinations (i.e., flashes of neon lights and a ladder), and headaches with occasional vertigo (twice/thrice weekly; duration: 1–24 hours; location: in the left frontotemporal region). Electroencephalography was reportedly normal. Previous brain magnetic resonance imaging revealed prominent sulci for her age, likely reflecting generalized volume loss.

The patient was referred for treatment with botulinum toxin to her right arm and shoulder. Initially, the treatment was helpful. However, at the time of presentation, the patient showed limited response to this therapy.

2.2. Past Surgical History

A right proximal femoral plate was placed in the 1970's (during patient's teenage years) for a presumed hip fracture. The patient had been unable to walk since this hip surgery and used a wheelchair for the remainder of her adult life.

Related to her CP, the patient underwent multiple corrective surgeries for dislocation of her right hip, nystagmus, left thumb, lengthening of the right Achilles tendon, kidney stone removal, atrial fibrillation, and myofascial pain syndrome.

Deep Brain Stimulator (DBS) placement as an adult resulted in good reduction of dystonia in the patient's right arm and leg with unilateral globus pallidus interna and subthalamic nucleus stimulation.

2.3. Medications

The patient had received treatment with fluticasone (dosage unknown), baclofen 20 mg TID, oxycodone 10 mg q HS, quetiapine 25 mg qd, and aspirin.

2.4. Social History

The patient lived with her elderly parent who assisted the patient with some activities of daily living, like dressing and

bathing, since the placement of the DBS. She was employed full time and was able to independently drive a car.

2.5. Mental Status Examination

During the patient's first presentation in the Clinic, the Patient Health Questionnaire (PHQ-9)=27 (>20: severe range of depression) [23] and the Generalized Anxiety Disorder Screener (GAD-7)=21 (>15: severe range of anxiety) [24]. Her subjective pain intensity rating was 9–10/10 at the time of presentation.

2.6. Physical Examination

At the time of presentation, the patient was not in acute distress. She was alert and oriented to person, place, and time. She was predominantly spastic on the right side. She presented with right arm and leg mobile dystonia. The right arm mostly exhibited ulnar flexion of the wrist and fingers flex; however, the right index finger was occasionally extended. She experienced difficulty in performing the Finger-Nose-Finger examination on the right side. Her right forearm was swollen. Distal and proximal dystonia were present. She lay with both hips and knees flexed. The passive range of motion of the right hip was limited due to the spasticity. However, there was no significant pain reported. She localized the pain throughout the entire lower extremity, with passive range of motion of the hip, and nontender to palpation of the hip and knee. She was unable to fire her toe flexors or extensors and had a palpable dorsalis pedis pulse.

3. Procedure

3.1. Session Format

The format of all sessions was identical: the patient entered the session, provided feedback using scales for anxiety and depression, and verbally reported the current and recent pain levels on a 0–10 scale. She subsequently spent approximately 10–20 minutes in an embodied, immersive VR-MVF experience of her choice, with a menu of options available. The patient sat in a wheelchair throughout all sessions. At the end of the session, the patient was requested to rate again the severity of her current pain using the same scale and describe any other observations. As part of the standard clinical care, the patient provided information using mood (PHQ-9) [23], anxiety (GAD-7) [24], and Sheehan Disability Scale [25, 26] quality of life scales, either at check-in or check-out.

In addition to the VR-MVF intervention, the patient received standard neuropsychiatric care, which included management using medications. Notably, there were no changes in medications during the course of VR-MVF. Weekly sessions of Phase 1 (described later in this article) were performed during the initial 24 weeks (6 months). After 6 months of weekly therapy (Phase 1), a different VR experience was used with monthly symptom assessments (Phase 2).

3.2. Software

3.2.1. Phase 1

A customized VR-MVF program was used, as previously described by our group [16, 19]. It presented the patient with the option of embodying either an entire avatar with an accompanying full-length mirror (Figure 1), or simply two upper extremities.

Arm movements were tracked by room sensors and mirrored visually to the patient. Hence, the movements of the right hand and wrist were controlled by the patient using a left-hand controller. Virtual left limb movements were either programmed to be synchronized to the right limb or left in a resting position independent of the right limb. The patient was able to explore a virtual world that included balloons and a tree, with the assistance of a physician moving her wheelchair in real space. When the patient hit a balloon, it would visually disappear, and audio feedback was provided in the form of a “pop.” An alternate activity for the patient was simply watching her own upper limbs moving without exploring the space.



Figure 1. Image of embodied avatar with full-length mirror.



Figure 2. Image of stone stacking exercise.

3.2.2. Phase 2

Customized augmentation of the avatar and gross motor activities, as well as integration of Leap Motion (Leap Motion Inc., San Francisco, USA) fine motor control was designed by the now defunct company Realiteer (REALITEER Corp., Belmont, CA, USA). This involved additional fine motor mirroring with a hand controller-free program, allowing the patient to voluntarily move the fingers and wrist in her left extremity, and experience finger movements virtually in her

right fingers. In this phase, the patient was also able to engage in varied mirrored gross motor activities, such as a stone stacking exercise (Figure 2), Tai Chi, or simply investigate a mirror while customizing an embodied avatar of her preference.

3.3. Meditation Experience

In addition to the aforementioned VR-MVF experiences, a commercial immersive VR-guided walking mindfulness meditation was intermittently delivered during both phases 1 and 2, using only head tracking from a non-embodied egocentric view, meaning the location of objects were identified relative to the perceived self. A subscription to the Psious Toolsuite (Psious, Barcelona, Spain), that included a head tracking immersive Walking Meditation, was used for the augmentation of mindfulness (Figure 3).



Figure 3. Image of guided mindfulness meditation in VR.

3.4. Hardware

Both phases used a commercially available HTC-Vive headset (HTC Inc., Taiwan) in the clinic office space, while the patient was seated and received stereoscopic images (Figure 4). The pitch, yaw, and roll, corresponding to the X, Y, Z positions of the head were tracked. In addition, the X, Y, Z positions of the upper limbs were tracked using an optical tracker. When presented, all avatar representations were female gendered and white, perceived from the egocentric view. The second phase included Leap Motion (Leap Motion Inc., USA) technology attached to the front of the headset that tracked fine motor hand motion and eliminated the need for handheld controllers in a certain range of motion. The walking meditation was delivered through a subscription service using Psious and a customized Samsung headset and phone.



Figure 4. HTC-Vive headset.

4. Results

Table 1. Subjective pre- and post-session intensity of pain, as well as measures of mood, anxiety, and quality of life, are summarized over the course of treatment sessions.

	Session Number							
	1	2	3	4	5	6	7	8
Pre-pain rating	10	9	8.5	7.5	8	7.5	8	8
Post-pain rating	9	8	8	5	5	5	5	5
% pain change*	10%	9%	7%	33%	38%	33%	38%	38%
PHQ-9	18	17	21	23	17	24	23	21
GAD-7	19	17	17	18	14	19	18	16
Sheehan Disability	na**	na	na	na	24	na	na	28

*Rounded to the nearest percent.

**Not assessed

Table 2. Subjective pre- and post-session intensity of pain, as well as measures of mood, anxiety, and quality of life, are summarized over the course of treatment month.

	Month Number					
	1	2	3	4	6	12
Pre-Pain rating	8.5	8	7.5	8	8.5	8
Post-pain rating	5	5	5	5	6.5	6.5
% pain change*	39%	38%	33%	38%	24%	19%
PHQ-9	23	21	17	12	20	13
GAD-7	17	19	11	11	21	10
Sheehan Disability	18	17	11	21	30	23

*Rounded to the nearest percent.

4.1. Phase 1: Weekly Assessment of Symptoms

4.1.1. Session 1

During a routine neuropsychiatric check-up, the patient reported increasing chronic pain that had developed in her back and arms in recent months. The management of this pain required the use of opiates. She had undertaken a new trial of physical therapy but did not feel this approach was helpful. Her pain and mobility problems in the right arm were worsening, with noted swelling in the right hand and forearm and erythema. During the visit, the patient was offered an available experimental VR-MVF experience for her pain. The risks, benefits, and alternative options were discussed and understood by the patient. She consented to the planned approach. During the procedure, the patient embodied a full avatar and experienced mirror movements of the upper and lower extremities while observing a reflection of herself in a virtual mirror for 5 minutes. After the VR-MVF procedure, the patient raised her right arm, which she reported she had been unable to do for many years, due to the problems in her shoulder. Her subjective rating of pain severity during the prior week up to the start of the session was 10/10. During and after the session, the reported pain was 9/10.

4.1.2. Session 2

The following week, the patient reported that the pain continued to be a 9/10, and she perceived her range of motion to be improved. During the next 20-minute VR-MVF with only two visual arms virtually present (i.e., without a full avatar), the patient reported a reduction in pain from a 9/10 to 5–6/10 during the exercise. However, after removal of the headset, her self-reported pain increased to an 8/10. The

patient reported that she experienced intense pain relief when her virtual right arm was extended laterally during the experience. There was also a noted decrease in swelling of the right forearm during the visit.

4.1.3. Session 3

The patient reported an increased ability to open and close her hand between sessions. Her pain at home, in bed, and at night was reportedly reduced to an 8/10, which she stated helped with sleep that week. Improvement in her range of motion was reported as stable, and she began exercising the right arm for the first time in two years. Permission by the neurologist was explicitly obtained to continue the VR-MVF trial. The rating of subjective pain intensity during and after the session changed from an 8.5/10 to an 8/10.

The family of the patient noted a decrease in the redness of the forearm. Moreover, a reduction in swelling from 8 inches to 7.5 inches was reported, as measured by the patient. During VR-MVF, the patient felt that her virtual left arm was distracting. Therefore, she requested to hide the second gaming controller and image (equivalent to her virtual left arm), in order for only her right upper extremity to be present in space, without an avatar body and unaccompanied by the contralateral limb. The patient engaged in balloon popping using a single limb.

4.1.4. Session 4

The patient noted sustained improvements since the previous visit, and the ability to straighten her right arm. During this visit, the patient performed a 20-minute upper extremity mirror therapy for the right side, as well as a brief lower extremity mirrored virtual experience on the right leg.

During the week, the level of pain reported was reduced to a 7.5–8/10. She then experienced an immediate decrease in pain to a 3–5/10 during the MVF session, a subjective feeling of relaxation and increased control, and improvement in the range of motion. In addition, she briefly performed a similar strategy for the left hand. The patient reported that the duration of the positive effects associated with the VR-MVF was approximately 3–4 days.

4.1.5. Session 5

The patient received an injection of steroids in her left wrist. She reported a pain intensity level of an 8/10 in her right hand and shoulder. Following 10 minutes of VR-MVF, the pain was reduced from an 8/10 to a 5/10, and increased relaxation in the limbs was reportedly experienced during the intervention. She repeated this exercise on the right lower extremity, where her pain was only a 3/10, without change in the rating. However, the patient reported a sense of increased control and relaxation.

4.1.6. Session 6

A fully embodied avatar was used, and upper/lower-body mirroring was performed. The patient reported an increase in relaxation on both sides of the body, an increased range of motion, and a sustained decrease in swelling. During the session, her pain decreased from a 7.5/10 to a 5/10, and the reported relaxation was increased. Increased movement of the right hand and arm, with spreading of the fingers was noted by the patient and physician. The patient reported using imagery at home to replicate the mirror therapy. A neurological examination noted greater mobility of the proximal arm and more control of her hand. The patient was able to better abduct her arm versus her previous ability to do so.

4.1.7. Session 7

The patient received 10 minutes of upper extremity VR-MVF through VR and 10 minutes of VR mindfulness training. The pain and distress at the beginning of the session was reduced from an 8/10 to a 5/10. Notably, the swelling remained limited. The report of the neurologist showed an improved ability to open and close her hand during the examination.

4.1.8. Session 8

The patient received both upper and lower extremity VR-MVF for 10 minutes, with good results and a subjective decrease in pain from an 8/10 to a 5/10, improved range of motion, and reports of immediate relaxation.

4.2. Phase 2: Monthly Assessment of Symptoms

4.2.1. Month 1

Following 6 months of weekly sessions in phase 1 with stable results similar to session eight, our group added new software and hardware that included a customized avatar and gross motor activities selected by the patient, as well as fine motor control that did not require handheld controllers. During the first application of a 10-minute bilateral upper and lower extremity VR-MVF with fine motor augmentation of

the fingers, the patient experienced increased relief compared to previous sessions, with an overall reduction in the level of pain from an 8.5/10 to a 5/10. During the examination, the patient was able to intermittently extend her fingers. The patient responded to the fine motor intervention within five minutes, with reduced pain, increased relaxation of the right hand, and tingling sensations. On the third week of treatment using the fine motor program, the right hand of the patient opened up for the first time with her fingers spread. The patient reported that she had not experienced this, while awake, in her adult life.

4.2.2. Month 2

Several VR mirror and mindfulness programs were customized to the height of the patient's wheelchair. The patient engaged with the headset for >40 minutes and reported a decrease in pain from an 8/10 to a 5/10. A continued increase in upper extremity mobility was noted. Moreover, she continued to remark on the pleasantness of having her right hand open for the first time.

4.2.3. Month 3

During the session, the patient reported a decrease in overall pain from a 7.5/10 to a 5/10. Some tingling was noted during the procedure in the left hand.

4.2.4. Month 4

The patient engaged in a stone stacking activity using the VR-MVR for 30 minutes, with a reported relief of pain and relaxation in the right hand. She stated that for the first time she was able to voluntarily lift objects (e.g., coffee cup) with her right hand at home.

4.2.5. Month 6

The patient reported good control of pain (i.e., a 5–6/10 for several days after the treatment). During the session, the reported change in pain was from an 8.5/10 to a 6.5/10.

4.2.6. Month 12

The patient continued to report improvement in pain, mood, sleep, movement, range of motion, and swelling in the right upper extremity. She reported being able to dress herself more comfortably and remarked that she was having brief pain-free moments at home. The levels of pain throughout the week ranged from a 3/10 to an 8/10. Of note, her sleep was reportedly improved. Pain intensity during the session with VR-MVF was relieved from an 8.5/10 to a 6.5/10. The patient initiated traditional MVF with occupational therapy the subsequent month.

4.3. Summative Symptom Change

The intervention showed consistent pain relief throughout the sessions. The percentage of pain relief during sessions ranged from 6.25% to 38.5%, with initial sessions showing less improvement compared to subsequent sessions (Figure 5). There appeared to be a mild effect in the early weeks of treatment, with an increasing effect observed over time, and some diminishing returns noted after 1 year.

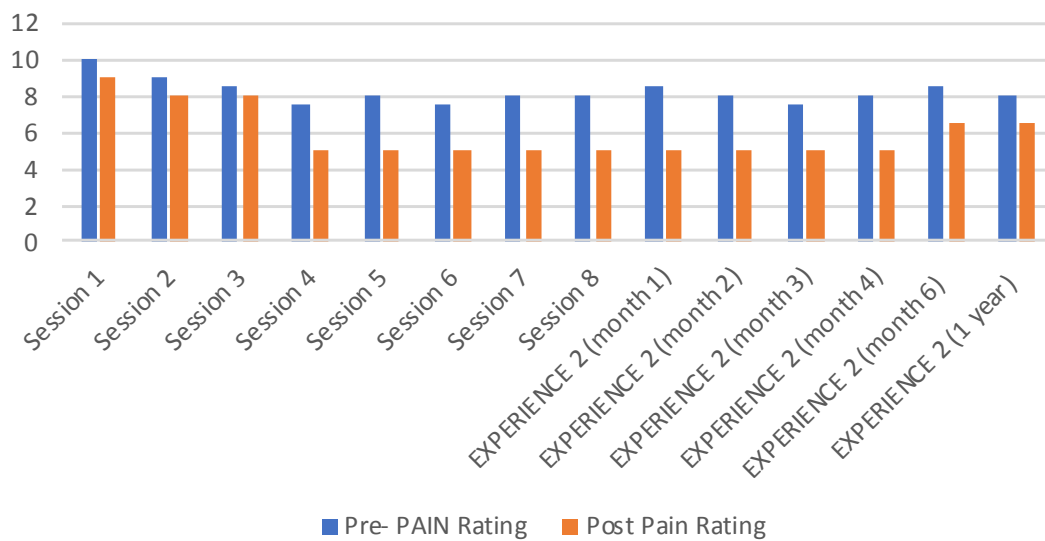


Figure 5. Pre- and post-pain intensity rating over time.

5. Discussion

This case demonstrates the safety and acceptability of delivering VR-MVF to an adult patient with CP in an outpatient setting. Over a period of 12 months, the patient did not experience episodes of cybersickness, despite having the vulnerability of a previous traumatic brain injury and despite even prolonged session durations later in therapy (i.e., ≥ 40 minutes). Rather, according to the patient, this approach was enjoyable and comfortable.

Initial feasibility challenges included working around physical constraints, such as a wheelchair. Lower extremity mirroring was limited by the shortcomings of the currently available software and hardware technology (e.g., lack of accurate foot tracking). The advantage of this VR-MVF treatment was the ease of use and reproducibility, especially for clinicians. Moreover, the approach was low-cost and commercially available.

Immediate pain reduction after the VR-MVF for this patient only slowly increased over the first three sessions and then plateaued. This may be evidence of an early kindling and dosage effect that was needed to create initial gains, which is consistent with the literature and phenomenon reported with PLP patients. The maximum results achieved were consistent over time and were comparable to the reported average pain reductions of 38%-40% in traditional MVF [14]. The last 6 months of MVF showed a drop off of pain relief, possibly indicating a desensitization process.

Subjective motor gains, as measured by physician and patient reports of improvement in motor control, flexibility, and range of motion, appeared early on and throughout phase I. It is assumed this is evidence of immediate activation of ipsilateral primary motor M1 pathways leading to increased control. Another burst in motor gains occurred in phase II when fine motor mirroring was introduced and the patient reported an ability to hold a cup and extend fingers. This

brings up the possible need for increasing novelty and precision of mirroring to maximize effects over time.

Screening assessments of disability severity, depression, and anxiety symptoms also showed no clinically relevant symptom improvement over the course of treatment, which may reduce the chance of motor and pain findings being explained by psychosocial confounds. The trend of the data did not indicate any sign of correlation between mood, anxiety, disability, pain, or motor improvement. Although it is disappointing that the patient's subjective improvements in pain and disability did not influence mood ratings. Especially in light of the finding in CP pain is correlated with quality of life [2]. In addition, the disability ratings appeared unaffected by the motor and pain gains.

The most notable negative feature of this VR-MVF intervention was the external dependence on the in-person treatment that developed over time. Continued administration of the treatment was required to maintain noticeable pain and motor effects since the duration of the pain relief was only two to four days. This brings up concerns around patients developing external locus of control and poor pain self-efficacy beliefs. However, developing a self-administered VR-MVF application for home use may solve this dilemma and offer added benefits. At home use would additionally provide opportunities to increase the dosage and frequency of VR-MVF, which could enhance effects. A self-delivered mobile home VR-MVF treatment would optimize patient autonomy and a decrease in healthcare utilization.

This case study has many limitations. First, all qualitative and quantitative measures used were subjective. Second, given the naturalistic setting, each VR-MVF session was non-standardized, with varying amounts of time and administered stimuli. Thus, these sessions were uncontrolled and difficult to compare. This case is also unique, considering that the patient had features not common to most adult hemiplegic CP patients. For example, she was non-ambulatory, had undergone placement of a deep brain

stimulation device, and experienced a previous TBI. Consequently, these factors may make these results hard to generalize to other CP populations.

This study highlights some of the gaps in knowledge and treatments for adults with CP. Most of the focus on innovation for CP is currently focused on pediatric populations. There is a paucity of reports or studies on the use of MVF or VR in adults with CP. To the authors' knowledge, this was the first study to investigate the use of VR or MVF for an adult with CP during the course of routine neuropsychiatric care. This study is also unique in the long period of time, over one year, that the case was followed. This duration of time is unusual for a reported VR intervention.

The present findings should inform others treating and researching CP to expand their consideration of rehabilitation to include MVF and VR not only in children but adults. This report is hoped to inspire industry and other stakeholders to invest and develop technologies using VR-MVF in CP and as well as other disorders, with an possible emphasis on mobile home use.

6. Conclusion

This case report, with results spanning over one year, supports a role for VR-MVP in improving upper limb function, pain, and dexterity in adults with CP. Further case reporting on this topic should continue in order to develop VR-MVP protocols for CP that can be tested in feasibility studies and controlled comparisons and rigorously examined for efficacy and scalability [26].

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