Pain Medicine 2015; 00: 00–00
Wiley Periodicals, Inc.

LETTER TO THE EDITOR

Two Virtual Reality Pilot Studies for the Treatment of Pediatric CRPS

Dear Editor,

The following letter describes two pilot studies testing the feasibility of immersive virtual reality therapy on pediatric patients with unilateral lower limb complex regional pain syndrome (CRPS). In these studies, patients completed target-hitting tasks in virtual reality using novel avatar bodies. Patients completed all sessions without adverse effects and both patients and parents were enthusiastic about the treatment. We discuss how function was tracked within and across sessions, and next steps.

Because virtual reality (VR) replaces sensory information from the physical world, users may partially replace their sense of presence in the physical world, or in their physical body. This quality of presence was first used to treat pain using distraction [1] and has also been used to produce relaxation or increased engagement (e.g., in physical therapy). A second quality that may be utilized in pain treatment is flexibility: the ability to change the relationship between a participant's appearance and/or actions in the physical world, and the appearance and actions that this participant perceives virtually [2]. Leveraging the flexibility of virtual reality allows the creation of avatars whose movements differ from that of the participants' own, allowing more radical interventions than mirroring the unaffected limb. Following Lanier's concept of homuncular flexibility [3], researchers have demonstrated that users can learn to identify with avatars that have very different bodies [4] and learn to control these avatars very rapidly [5]. We propose that using such novel bodies may also be therapeutic for pain.

Methods

Four patients with pediatric CRPS, confirmed by Budapest Criteria [6], were enrolled in this study, after institutional review board (IRB) approval, consent, and assent. All patients were receiving concurrent multidisciplinary therapy including physical and occupational therapy, psychological support, and medical visits. All therapies, including medications, were kept constant throughout the study period.

We manipulated the flexibility of the relationship between tracked and rendered motion in two ways. First, we altered how much effort must be exerted to take action in the virtual world, by increasing the gain between participants' movements in real life and their avatars' movements in the virtual world. Second, we altered which of the patients' limbs controlled the limbs of the virtual body, switching arms with legs.

Participants were seated and wore an immersive virtual reality headset that provided stereoscopic images. The pitch, yaw, and roll, and X, Y, and Z position of the head were tracked, and optical X Y Z trackers were also worn on both ankles. Participants also received spatialized audio feedback ("pops") when interacting with stimuli in the environment. Finally, haptic feedback was available through the floor, which vibrated slightly when low-frequency audio was played. All avatars were silver-colored and undetailed, and could be viewed only from the first person perspective. A sequence of balloons was programmed to appear randomly in the center of the room in front of the participant in a four-foot-wide plane scaled to the upper limits of the avatar's arm's reach. If a participant hit a balloon, audio feedback was provided in the form of a loud "pop" and the floor vibrated slightly. If a balloon were not popped within 5 seconds, it would disappear silently. Participants returned to the lab for six successive sessions.

The first pilot study consisted of two conditions: the normal condition, in which participants' tracked legs controlled their avatars' legs in a one-to-one relationship (Figure 1, left) and the extended condition, in which the gain of participants' leg movements was increased by a factor of 1.5, such that a moderate kick in the physical world gave the avatars' legs great range (Figure 1, middle). Participant A was a 17-year-old male with CRPS in the left leg, and Participant B was a 13-year-old female with CRPS in the right leg, both right-leg dominant. In the second study, we added a third, switched condition, in which participants' physical legs controlled their avatars' arms (Figure 1, right side). Thus, a kick near waist height in the physical world would allow the avatar's arm to be raised over the head. The procedure and apparatus in Study 2 were otherwise identical to those described in Study 1. Participant C was a 14-year-old male, left-leg dominant, and Participant D was a 16-year-old female, strongly right-leg dominant. Both were diagnosed with CRPS in the right leg.

Results and Discussion

From a clinical viewpoint, participants were remarkably calm and engaged while in the study. This was quite different from their behavior during standard physical therapy sessions, where even very slight movement was often associated with wincing, verbal statements such as "Ahh" and "Ouch," drawing back of the limb, and pausing. In contrast, during VR treatment, they did not complain of pain, arrived eager to engage, and tolerated the therapy well, actively moving the affected extremity during the entire 5-minute session for each two or three

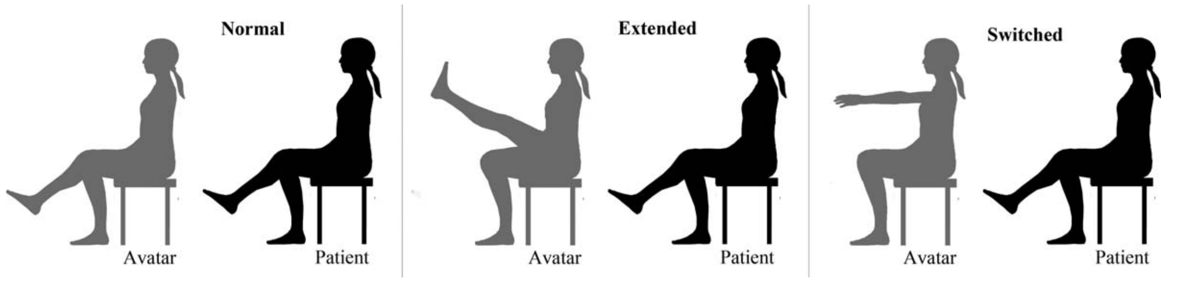

Figure 1 The left image shows the relationship between patient (black) and avatar (gray) for the normal condition, where the patients' legs controlled the avatars' legs in a one-to-one relationship. The middle image shows the extended condition, where the patients' leg movements were increased by 1.5× in the avatar, allowing a greater range of balloons to be popped with less effort. The right image shows the switched condition, in which participants' physical legs controlled their avatars' arms.

conditions in all but one case. This is felt to be significant as, during their routine physical therapy sessions, although the therapy session lasted for 30–60 minutes, the subjects would only typically be active for 2–3 minutes at a time before wincing, complaining of pain or needing to rest during an individual exercise. Subjects completed 96% of the requested activities. Some pointed out program suggestions and provided ideas for more realistic scenarios. Participants' qualitative responses were generally positive, describing the game as "cool," "simple but interesting," or "motivating, trying to beat my score from last time." The tracking data in Figure 2 (left) is representative and may demonstrate that participants moved their injured legs for increasing distances as they improved. (Fluctuation of distance/foot movement was as expected in the condition given daily variability in function as well as pain).

Although the study described does not have enough participants to draw conclusions about pain efficacy, the measures described may provide a path for future treatment for pediatric pain participants using the flexibility provided by VR. We confirmed that VR was safe and well tolerated, and did not worsen pain or physical

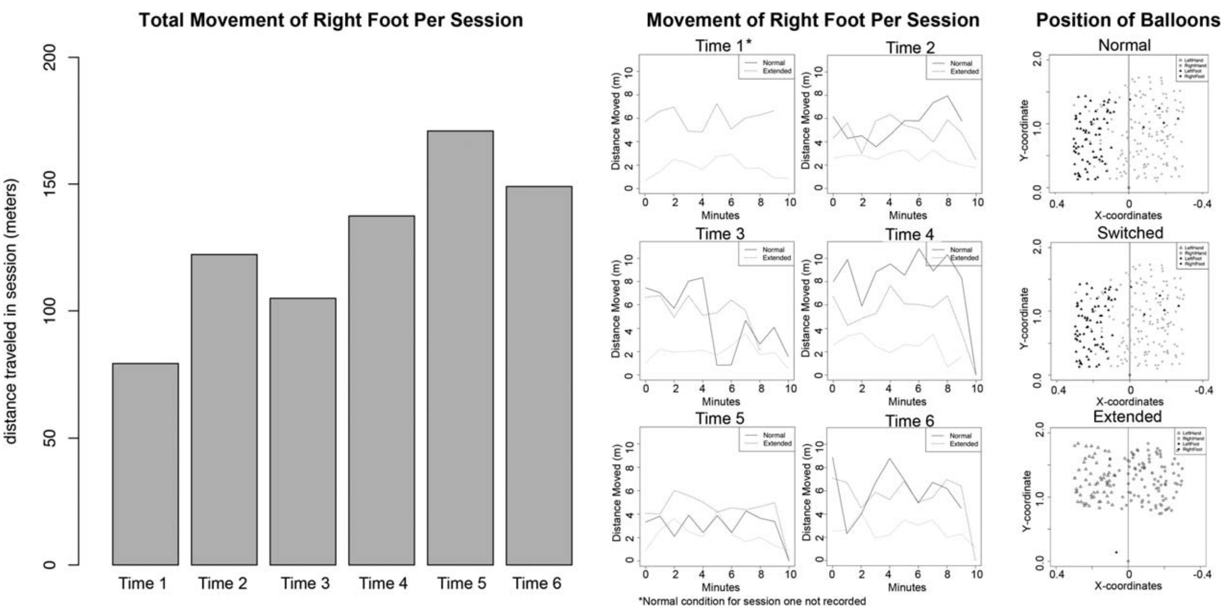

Figure 2 The plot on the left indicates the average distance traversed to reach balloons popped by participant D's injured leg for each session. The plots in the middle indicate the average distance traveled by the injured limb, in each condition, for participant D, in 30 second increments. All sessions are shown. The plots on the far right show the location of each balloon popped by participant D, by each leg, in each condition, during session 1.

functioning. We also found that participants would tolerate disconnects between tracked and rendered movement.

In addition to demonstrating feasibility, we have illustrated three methods of tracking increased function. The first and second, (see Figure 2, left and center) measure movement. The third, illustrated in Figure 2, right, tracks the position of balloons popped by each limb, allowing us to visualize how mobile the affected and unaffected limbs were, respectively. Note that for the extended and switched conditions, the first and second tracking conditions reflect the amount of movement in the physical world required to reach the balloons popped in VR. In future, rather than estimating movement by balloons popped, actual movements will be recorded.

A larger sample size in the future will allow limb dominance and affected limb side to remain consistent. To take into account order effects, the order of conditions should be randomized. In addition, the very fact that the experience was so engaging to patients requires us to separate their enjoyment of the experience from long-term improvement when possible. Finally, because this treatment occurred simultaneously with other multidisciplinary therapies, we cannot attribute improvement to virtual reality alone; rather, this pilot study is a proof of concept.

Our results demonstrate that VR therapy is safe and feasible for pediatric patients suffering from CRPS, and that using a more flexible mapping of movement is an option. Future directions include the investigation of what kinds of mapping (mirroring, switching arms and legs, increasing gain, etc.) are best for increasing movement, and/or decreasing pain. We also intend to investigate how this treatment can be made more readily available. The advent of new commercial virtual reality systems means that at home systems are now becoming technically feasible, and the availability of lighter weight headsets means that therapy sessions can extend for longer periods of time without discomfort. Such systems allow patients access to therapy and the ability to maintain long-term motivation. As our next step, we will design a portable system that can be used in the clinic and at patients' homes to begin to answer these questions.

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