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A Novel Application of Virtual Reality for Pain Control: Virtual Reality-Mirror Visual Feedback Therapy

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Additional information is available at the end of the chapter

1. Introduction

Virtual reality is state of the art technology, but its concept can be found in many fields even in the past. These technologies, such as computer graphics, simulation, and human-computer interfaces have all led to the evolution of virtual reality technology. The virtual reality technology developed in the 1960s is similar to what we see in the present day. In the fields of computer graphics, Ivan Sutherland created the pioneering virtual reality system, *The ultimate display* in which he used computers for the designing, construction, navigation and habitation of virtual worlds. He also developed a head mounted display which was designed to immerse the viewer in a visually simulated 3D environment. During the 1960s and 1970s, virtual reality technology had been applied to aerospace and military fields. The US Air Force established a laboratory at Wright-Patterson Air Force Base in Ohio and created flight simulators for high speed military aircraft. This resulted in the construction of the Super Cockpit in the 1980s which Tom Furness created as the director of this project. It is widely credited that Jaron *Lanier*, director and founder of *VPL* (*Visual Programming Language*)**,** coined the term virtual reality in 1989 to bring all of the virtual projects of VPL, such as eyephone, dataglove and datasuit under a single term. In 1990 the human machine interfaces for teleoperators and virtual environments conference was held in Santa Barbara, CA and *virtual reality* was given as a general term for all related technologies.

Virtual reality (VR) consists of indispensable elements including a virtual world, immersion, sensory feedback, and interactivity. The distinguishing characteristic of VR is a sense of immersion that occurs from the user interacting with a VE using multimodal stimuli, such as visual, auditory, and tactile stimuli. Another distinguishing characteristic is that VR gives

the illusion that objects that do not exist in the real world exist inside a computer-generated VE. Virtual reality technology is used in a variety of fields and possible medical application has attracted keen interest. Potential benefits have been reported in applications such as treatment of post-traumatic stress disorder following the terrorist attack on the World Trade Center [1], rehabilitation following a stroke [2], and disability management following accidents or surgery [3]. Virtual reality technology holds the promise as an analgesic modality in diverse ways. There is growing evidence about the successful application of VR technology to alleviate acute pain during medical procedures. Recently, the application of VR for chronic pain control has also been gaining attention. There are excellent review articles about this issue [4] [5].

This manuscript consists of three chapters. Chapter 1 presents an overview of VR technology applied to pain treatment, especially focusing on the treatment of chronic pain such as phantom limb pain. The scope of the topic in chapter 1 expands into a new approach for the treatment of phantom limb pain. Because technology is advancing rapidly, it is now possible to create a prosthesis that allows patients to control it by their thoughts alone. Perhaps if patients with phantom limb pain could use a high-tech prosthesis that they can directly control with their thoughts, phantom limb pain could be relieved. Chapter 2 introduces the virtual reality-mirror visual feedback (VR-MVF) therapy that we have developed and its analgesic efficacy in patients with complex regional pain syndrome (CRPS). Chapter 3 introduces our VR-MVF system for home use. Although the advanced MVF with VR technology showed increased analgesic efficacy and benefit, few patients can benefit from this treatment. The reason why VR-MVF has not yet become popular for clinical practice is due to the cost and the elusiveness of the technology required for VR. We have been working on two projects to resolve these problems. The drawbacks of virtual reality should be considered, because it will limit the applicability of VR for wide-spread use. Drawbacks of VR can be divided into two categories, technology-related disadvantages and VR-related side effects. Technology-related disadvantages include the high cost and the complexity of the system which requires extensive knowledge of VR for its repair and maintenance. For example, the hardware including the head-mounted displays, data-glove and motion capture system, requires frequent adjustments to be made for maintaining the sense of immersion. Particular concern for VR-related side effects is necessary because these systems are occasionally applied to patients with impairment. These patients may have a higher susceptibility to side effects. There are also concerns about the social impact that virtual environments affect on people, such as the psychological effects of prolonged usage. As an example of social disadvantage, some concerns are raised on desensitization. Although virtual reality technology is applied to systemic desensitization therapy which is a technique used to treat phobias and fear, in extreme cases there are concerns that users could fail to recognize the consequences their actions in virtual environments may cause in the real world. VR-related side effects include *Cybersickness* and *Aftereffects*. Cybersickness is a form of motion sickness. Symptoms include eyestrains, blurred vision, headaches, vertigo, imbalance, nausea and vomiting. Cybersickness is believed to occur as a result of conflicts between visual, vestibular and

proprioceptive perception. Symptoms of Aftereffects include disturbed locomotion, postural instability, fatigue and drowsiness. The users adapt to the sensorimotor requirements in virtual environments (VEs), and after leaving VEs they must readapt to the sensorimotor requirements in the real world. Aftereffects is believed to occur as a result of a lag in the sensorimotor response recalibration.

1.1. Virtual reality and pain management

Virtual reality technology as an analgesic modality was initially applied to attenuate pain perception during painful medical procedures. Hoffman *et al.* first reported that VR could alleviate pain perception during painful burn care in adolescent patients [6]. The application of VR for pain control during burn care has been the most intensively studied application [7-8]. Other procedures to which VR has been applied include dental procedures [9] and intravenous placement [10]. Virtual reality technology with a head-mounted display allows the user to feel as if they are present in the VE, and interaction with the VE through manipulation strengthens the user's immersion. With strong immersion, the user's attention is focused on the VE, which subsequently can take the user's attention away from pain. This is the distraction theory, which is one of the hypotheses of the mechanism of VR analgesia. Virtual reality analgesia has been speculated to be the result of distraction. Recently, advancement in neuro-imaging studies has revealed how VR distraction modulates pain processing in brain regions known as the pain matrix [11][12]. Neuroimaging studies have identified several brain regions that are consistently activated during nociceptive stimulation. These brain regions are referred to as the pain matrix which includes the anterior cingulate cortex (ACC), the insula, the thalamus, and the primary (S1) and secondary (S2) somatosensory cortices. Hoffman et al conducted a study using fMRI in healthy volunteers to investigate the associated changes in pain-related brain activation during nociceptive thermal stimulation and compared these results under conditions of no analgesia, opioid (hydromorphone) analgesia alone, VR distraction alone, and opioid analgesia combined with VR distraction [12]. VR distraction alone significantly reduced subjective pain and significantly reduced pain-related brain activity in the insula, thalmus, and S2. Combined opioid with VR distraction reduced pain reports more effectively than did opioid alone for subjective pain.

Although interests and expectations in the application of VR for the treatment of chronic pain are growing, few studies about the analgesic efficacy of VR in patients with chronic pain have been reported. The application of VR to chronic pain treatment has not progressed further due to the lack of complete understanding about the mechanism of VR analgesia. We still do not know how we can use VR technology to build a system for providing analgesic efficacy for patients with chronic pain. However, a novel approach is to enhance the existing treatment, which is already known to have some analgesic efficacy for chronic pain, with VR technology. In this context, VR technology has been successfully applied as VR-hypnosis [13], VR-MVF therapy for phantom limb pain [14], and treatment for CRPS [15]. Hypnotic analgesia has gained special attention as an analgesic modality [16]. Oneal *et al.* integrated hypnotic analgesia with VR technology and applied the combination

in the treatment of chronic neuropathic pain [13]. A patient with a 5-year history of C4-quadriplegia and upper extremity neuropathic pain received an audio recording of a hypnotic induction, i.e., suggestions for pain relief. After a 6-month trial of VR-hypnosis, the patient's rating for pain and discomfort dropped more than 30%. Another example of the application of VR to pain treatment has been shown by Sarig-Bahat *et al*. [17]. They developed a VE in which the cervical range of motion (CROM) of a patient with neck pain was assessed during a simple but engaging gaming scenario and compared with that of individuals with no neck pain. The participants' task in the VE was to spray a fly with a spray canister. Once a fly was sprayed, it vanished and a new target appeared within a larger ROM. The results of a single session revealed increasing CROM and decreased neck pain. They speculated that VR may play a role in overcoming the fear of motion via pain distraction, which subsequently improves CROM and results in pain reduction. Patients with chronic pain avoid moving the affected part of the body for fear that it will exacerbate the pain; this is the so-called fear-avoidance model [18]. Lowering fear-avoidance has been shown to be effective for the treatment of chronic back pain [19]. This type of approach is also known as cognitive behavioral therapy, the beneficial effects of which have been shown in patients with chronic pain [20]. The graded exposure of cognitive behavioral therapy *in vivo* can improve disability through reducing anxiety, which results in decreased pain in patients with CRPS [21].

1.2. Virtual reality for phantom limb pain

Virtual reality allows the user to experience a computer-generated VE by using advanced technology such as a head-mounted display with tracking systems. Interestingly, the application of VR to chronic pain treatment was initially made without the help of these cutting-edge technologies. Ramachandran and Roger–Ramachandran introduced mirror visual feedback (MVF) therapy with a virtual mirror box for the treatment of phantom limb pain and reported its promising analgesic efficacy [22]. A vertical mirror was placed and an upper limb amputee was asked to place his normal hand on one side (the reflecting side) of the mirror and to look at the reflection of the hand optically superimposed on the felt location of the phantom. If the subject moved his normal hand, he not only saw his phantom move but felt it moving as well. In some cases, this relieved painful cramps in the phantom limb. A distinguishing characteristic is that the VR gives the illusion as if objects that do not exist in the real world exist inside a computer-generated VE. This outstanding characteristic of VR makes it possible for missing extremities to emerge inside the virtual world. Thus, it seems reasonable to integrate Ramachandran's MVF therapy for phantom limb pain with VR technology. Murray *et al*. developed an immersive VR system that transposes movements of an intact limb onto that of a virtual limb in a computer-generated VE [14]. Their system contains a head-mounted display, data glove and sensors for an upper limb, sensors for lower limb, and a Fastrak tracking device for monitoring the movements of head, arm, and legs. Three patients with phantom limb pain, two with upper limb and one with lower limb amputation, who participated in two or five treatment sessions over a 3-week period, reported a reduction in their pain.

Mirror visual feedback therapy including VR-MVF is not always able to induce beneficial analgesic effects for patients with phantom limb pain. Although most patients feel reduced phantom limb pain during the therapy, pain relief could be sustained in only a limited number patients after the therapy. It is speculated that MVF decreases phantom limb pain by restoring the shrunken somatosensory area (reorganization) that formally corresponded with the deafferentiated limb. Because technology is advancing rapidly, if patients with phantom limb pain had a prosthesis that they could directly control, and, moreover, if patients could feel feedback sensations such as haptic or proprioceptive feelings in response to their motor commands, it would help to restore the normal cortical map and phantom limb pain would be dramatically relieved. Moreover, unlike with MVF, patients with phantom limb pain could wear the high-tech prosthesis and use it in their daily life, which has the advantageous effect of restoring the normal cortical map sooner and subsequently providing long-lasting pain relief. This means that such a high-tech prosthesis could be a new approach for the treatment of phantom limb pain.

It is known that different mechanisms are underlying phantom limb sensation and phantom limb pain. Blakemore *et al.* explained phantom limb sensation using a forward model [23]. A forward model uses an efference copy to predict the sensory consequences of the motor commands and compares this with the actual sensation of the movement. They suggested that the normal experience of the limb is based on this predicted state, rather than the actual state. Even in the case of missing limbs, motor commands lead to the prediction of the movement that results in phantom limbs sensation. Approximately 50-80% of all amputees have phantom limb pain [24]. Both peripheral and central mechanisms and even psychological factors have been implicated as the mechanisms of phantom limb pain [25]. Flor *et al.* especially focused on the pain memory established before the amputation as a powerful elicitor of phantom limb pain. They explained that if a somatosensory pain memory has been established with an important neural correlate in the spinal and supraspinal structures, such as in the primary somatosensory cortex, subsequent deafferentation and an invasion of the amputation zone by neighboring input may preferentially activate cortical neurons coding for pain [25]. Meanwhile, reorganization in the primary somatosensory motor cortex has been strongly correlated with phantom limb pain [26]. However, no conclusive explanation about why reorganization in these brain regions causes phantom limb pain has been made. The adult brain was formerly recognized as a hard-wired organ but recent neuroscientific evidence revealed that substantial plastic changes can occur. It is also known that this plasticity can be reversed. Birbaumer *et al.* showed that suppression of afferent input from the amputation stump by brachial plexus anesthesia eliminated both cortical reorganization and phantom limb pain in half of the subjects [27]. In the other half, both cortical reorganization and phantom limb pain were unchanged during upper extremity anesthesia. The authors suggested that in some amputees, cortical reorganization and phantom limb pain may be maintained by peripheral input, whereas in others, intracortical changes might be overriding. The approach for restoring this reorganization into a normal state is expected to be a promising analgesic modality [28]. Lotze *et al.*, using functional magnetic resonance imaging, investigated the

effect of prosthesis use on phantom limb pain and cortical reorganization [29]. Patients who used a myoelectric prosthesis that provides sensory, visual, and motor feedback showed decreasing phantom limb pain that was subsequently correlated with less cortical reorganization compared with patients who used a cosmetic prosthesis or no prosthesis.

1.3. A new treatment approach for phantom limb pain: A brain-controlled prosthesis

The idea of direct brain control of a prosthesis is mainly aimed to improve the functionality of a prosthesis rather than to treat phantom limb pain, which subsequently helps the disability of amputees. However, because phantom limb pain tremendously impairs the amputees' quality of life, the analgesic efficacy provided with a brain-controlled prosthesis on phantom limb pain has also gained keen interest. However, if a high-tech brain-controlled prosthesis can only make movement in response to patients' motor intention and no sensory feedback other than visual feedback can be obtained, there may be no significant difference between MVF therapy and a brain-controlled prosthesis in terms of analgesic efficacy. However, even if this were the case, a brain-controlled prosthesis still might have some advantage over MVF. To construct the image of the missing limb with the reflection of a mirror image in MVF therapy, an amputee makes a motor command of the healthy limb. However, with a brain-controlled prosthesis, only the motor-related brain region for the side of the missing limb is activated. Because there is communication between the two brain hemispheres, activity on one side is known to inhibit activity on the opposite side [30]. In this context, brain activity in the case of a brain-controlled prosthesis might be more strongly activated than that in MVF, which subsequently may be favorable from the point of view of restoring normal brain state. Because delivering sensory feedback as a consequence of motor commands improves the functionality of a prosthesis, researchers working on a brain-controlled prosthesis have been trying to deliver effective feedback. This will give tremendous beneficial effects on the analgesia that a brain-control prosthesis is expected to provide.

To make a brain-controlled prosthesis move, the first step is to extract voluntary commands. Once motor commands are extracted, the next step is to deliver the extracted information (motor commands) to the artificial limb (prosthesis). Ideally, the last step is to deliver the haptic and proprioceptional information as sensory feedback that the patient expects to feel as a consequence of motor commands. Sensory feedback is expected not only to improve the functionality of a prosthesis but also to decrease phantom limb pain. There are several approaches for the extraction of motor commands, incuding electromyographic (EMG)-based controls with targeted reinnervation [31] [32], a brain (cortical)-controlled neuroprosthesis [33] [34], and a longitudinal intrafascicular peripheral interface [35].

For example, an EMG-based control as a recording modality of motor commands has the advantages of simplicity and noninvasiveness because of its surface electrodes. The current detectable by an EMG-based control is larger than that detectable by a brain (cortical)-controlled prosthesis. Meanwhile, a brain-controlled prosthesis needs an invasive

intracranial electrode. Hochberg *et al*. have implanted intracranial electrodes in the human motor cortex as a prosthetic control and also reported that a patient with quadriplegia could use neural control to open and close a prosthetic hand [34]. There are considerable problems, including complexity and biocompatibility, which have to be solved before a brain (cortical)-controlled prosthesis can be used as a modality for prosthesis control.

The EMG-based prosthesis which is controlled with myoelectrical signals from a remaining pair of agonist-antagonist muscles in the amputated limb, provide very limited motion. To overcome this drawback, Kuiken *et al*. have developed targeted reinnervation for enhanced prosthetic arm function [31]. Surgery is performed on a patient with a traumatic amputation. Residual peripheral nerves of the brachial plexus are transferred to the patient's pectoral and serratus muscles. When the patient thinks about closing his hand, for example, the amplified myoelectrical signal from the pectoralis muscle causes constriction that is used to control the closing movements of the computerized prosthesis. The targeted muscle reinnervation technique allows an amputee to intuitively control a prosthesis. Another outstanding characteristic of Kuiken's technique is targeted sensory reinnervation that can provide sensory feedback as a result of motor intention. The anterior chest skin that was overlying the targeted muscle reinnervation site is denervated and reinnervated with the ulnar and median nerves. A patient's intention to move the prosthetic hand causes constriction of the anterior chest muscle and simultaneously, the skin on the surface of the constructed muscle activates the reinnervated nerves that subsequently provide the feeling that the patient's hand was touched. Kuiken's technique can allow amputees to directly control a prosthesis with their intentions and delivers sensory feedback as a consequence of motor commands. Before the targeted reinnervation surgery, one amputee had severe phantom limb pain but it resolved after 4 weeks of treatment following the surgery. Motor commands can be extracted by interfaces with the peripheral nervous system. Horch *et al*. implanted longitudinal intrafascicular peripheral interfaces (LIFEs) into the median nerve of three amputee subjects [36]. They reported that the motor signals recorded using LIFEs can be used to control a robotic system. These LIFEs also seem to be able to provoke sensory feedback. In a preliminary study on amputees conducted by Horch *et al*., they reported that stimulating different afferent nerves using LIFEs could provide sensory feedback [37].

Micera pointed out that the peripheral nervous system-based control of a prosthesis using LIFEs may help to modify the plastic reorganization after the amputation and restore brain areas to a normal state, which subsequently is expected to decrease phantom limb pain [35]. Dietrich *et al*. reported that sensory feedback prosthesis reduced phantom limb pain [38]. In their system, the pressure information measured by a sensor located in the bend between the thumb and index finger of a myoelectric prosthesis was transformed into electrical stimulation patterns by a microcontroller. Then electrocutaneous stimulus was delivered as sensory feedback to the skin of the subject's stump. Two-week training with this system provided significant improvement in the functionality of the prosthesis and reduced phantom limb pain. Although the sensory feedback in Dietrich's system was not exactly haptic or proprioceptive sensation in response to the motor intention, it still could provide considerable analgesia. Thus, if real sensory feedback such as haptic or propriocetive

sensation could be provided in the near future, phantom limb pain could be completely relieved. However, both peripheral and central mechanisms and even psychological factors have been implicated as the mechanism of phantom limb pain, so some patients may still not have pain relief from a brain-controlled prosthesis.

2. Application of virtual reality for chronic pain treatment of patients with complex regional pain syndrome

Complex regional pain syndrome includes a variety of pain conditions with both motor and autonomic symptoms [39]. The underlying pathogenesis is not yet fully understood, which makes it difficult to establish effective treatments. Alternative analgesic modalities have been actively sought for the treatment of CRPS. Ramachandran introduced MVF therapy [22]. CRPS type 1 shares many strikingly similar characteristics with phantom limb pain [26] [40] [41]. Mirror visual feedback therapy is expected to provide analgesic effects for patients with CRPS. The advanced MVF system with virtual reality technology (VR-MVF) contains very specific target-oriented motor control tasks and enables subjects to feel engaged and rewarded, thus encouraging them to repeat the exercise with intensity. In this regard, VR-MVF has tremendous potential as a non-invasive alternative analgesic modality for CRPS.

2.1. Virtual reality-mirror visual feedback system

A personal computer-based desktop VR system was developed for MVF therapy. The system contains a personal computer (operating system: Windows XP Professional SP2; central processing unit: Intel Core 2 Duo 3.16 GHz; graphics: Radeon HD 4679), a CyberGlove (Immersion Co.) as a hand input device, a Fastrak device (POLHEUMS Co.) as a real-time position and motion tracker, and a 20-inch desktop monitor (EIZO FlexScan SX2761W, EIZO Nanao MS Corp. Japan). A VE was developed using commercially available software, Autodesk 3DS Max. The system is shown in Figure 1. In the VE, three objects of different sizes and shapes are initially located on the table with a back shelf. The forearm and hand on the affected side appears on VE and every movement or any laterality of the real arm can be precisely reproduced. The movement of the fingers and wrist of the virtual hand is simulated by the CyberGlove, which is attached on the non-affected side because pain is induced if the affected hand is used. The Fastrak position tracker that determines the position and orientation of the virtual arm is mounted on the affected side. In the VR-MVF system, a virtual forearm moves in the same manner as the affected side, but the hand and finger motions are simulated by the non-affected side. This is the biggest difference between MVF therapy with a mirror box and VR-MVF therapy. Recently, we renovated our VR-MVF system (Figure 2). A 50-inch Panasonic TH-P50VT5 display monitor and 5DT Data Glove 5/14 Ultra hand input device were used. A VE was developed using OpenGL (Silicon Graphics) as the application program interface and a three-dimensional model was constructed by Metasequoia. The most distinguishable change was made in the physics simulation. Havok Physics (Havok Co.) was used as the physics engine that makes objects in the VE roll and bounce in a very realistic manner on the screen.
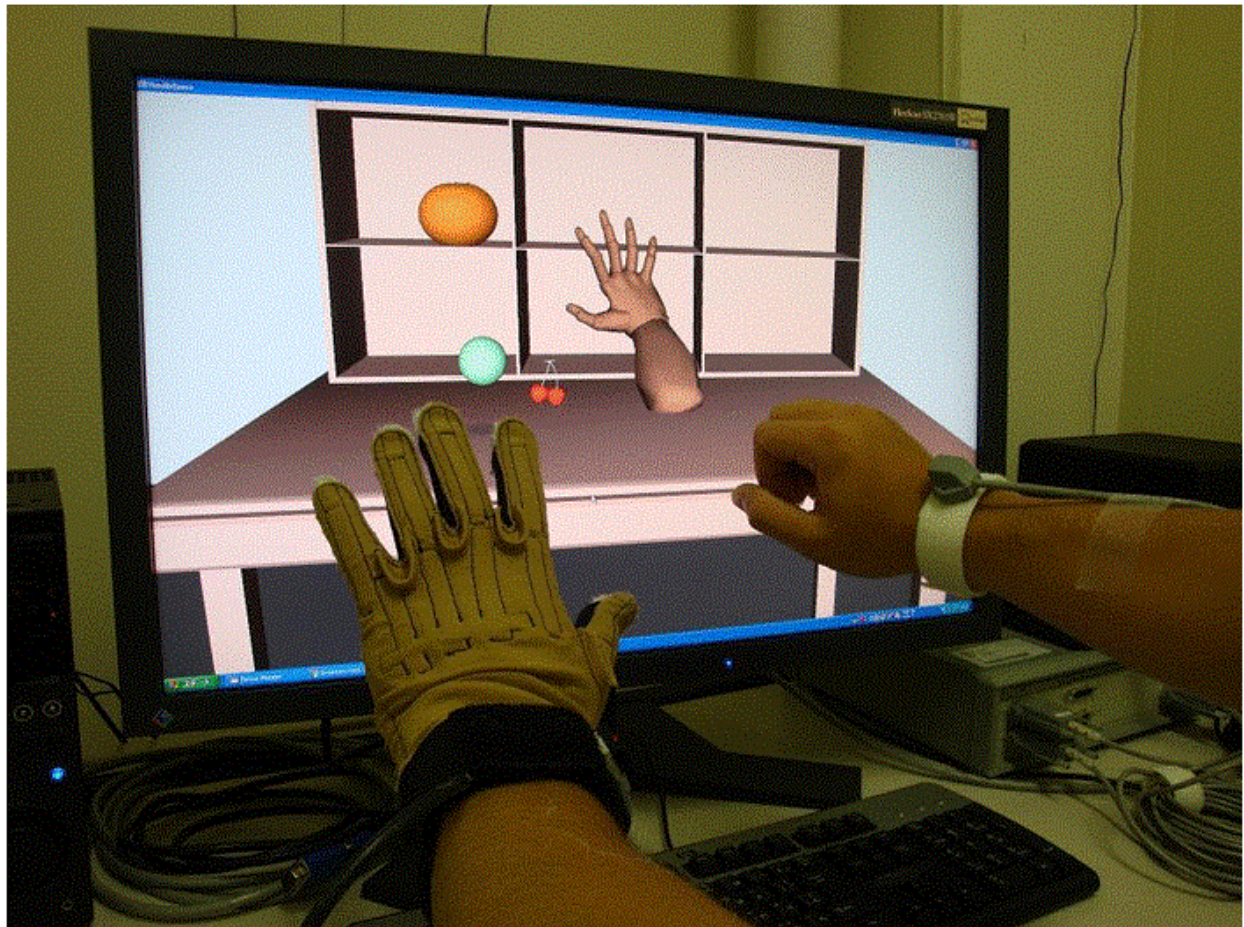
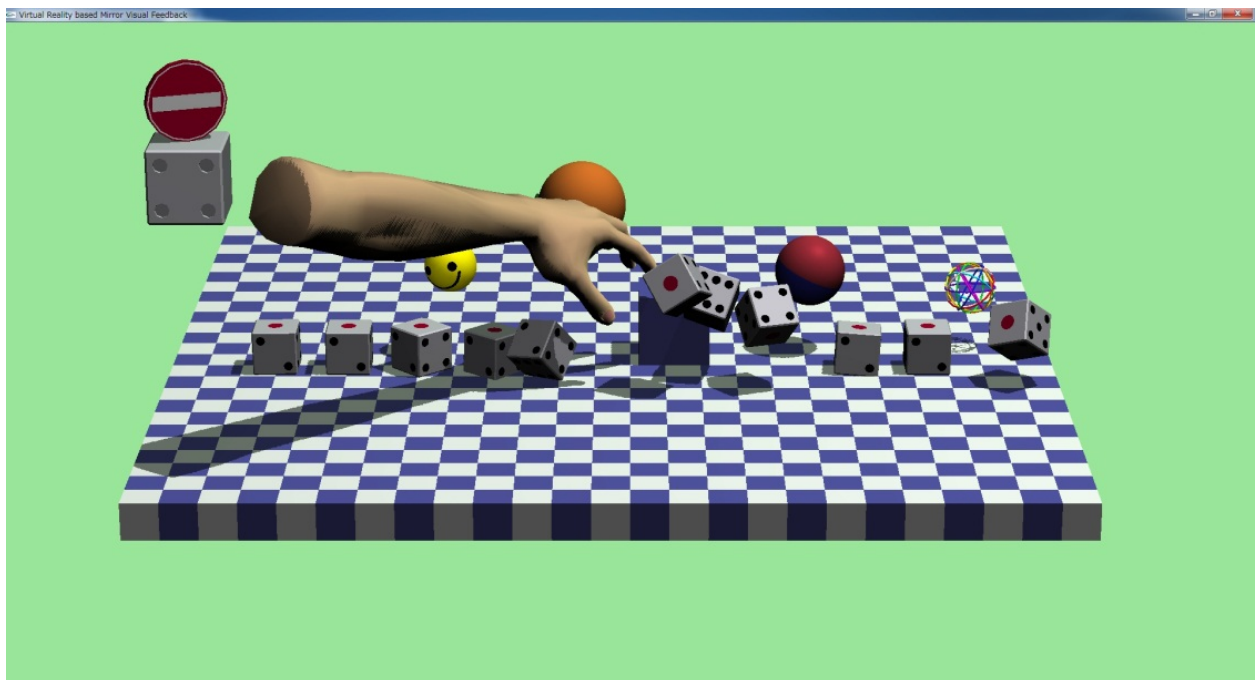**Figure 1.** Virtual reality-mirror visual feedback therapy in Okayama University Hospital

Figure 2. The renovated version of virtual reality-mirror visual feedback therapy

2.2. Application for patients with complex regional pain syndrome

Virtual reality-mirror visual feedback exercises are target-oriented motor control tasks. The sequences of hand exercises consisted of the movements of reaching out, grasping, transferring, and placing. Five patients with CRPS of the hand attended VR-MVF therapy. The therapy was given once a week at an outpatient pain clinic in Okayama University Medical Center, where the VR-MVF system was set up. In each therapy session, no time limit was set. Analgesic medications were continued at the same regimens as before the therapy. If patients reported an increase in pain intensity or related side effects of VR-MVF therapy, treatment was immediately cancelled and additional drugs or treatment were administered. However, if patients reported decreased pain intensity, medication was adjusted or stopped as directed by the patient. Subjective pain was evaluated according to a visual analogue scale (0 = no pain, 100 = worst pain) before and after each treatment session. All patients reported spontaneous pain in the affected limb that increased with movement. The pre-treatment score on the visual analogue scale (64 ± 14) (mean ± SD) decreased to 31 ± 26 after consecutive treatment sessions. Four of the five patients (80%) showed 50% reduction of the pre-treatment visual analogue scale value. The analgesic effect provided by VR-MVF therapy in five cases of CRPS is shown in Figure 3. All cases showed a short-term reduction in pain intensity (before-and-after comparison of the visual analogue score in each session) and four of the five cases showed consecutive decreases of visual analogue scale score, which led to a 50% reduction of the pre-treatment value after respective treatment sessions.

Effective pain reduction (50% reduction) was accomplished after the third treatment session in Cases 1 and 2, the fourth session in Case 3, and the eighth session in Case 5.

In this preliminary work, our VR-MVF therapy was able to provide successful analgesic efficacy: 80% of patients showed more than a 50% reduction of pain intensity after three to eight consecutive treatment sessions. It is worth noting that all five patients were in a chronic state of CRPS, which is known to be difficult to treat by original MVF therapy with a mirror box. In two patients, the analgesic effect continued even after cessation of the therapy. Moreover, none of the five patients in the present study reported experiencing any related side effects. Our result showed that VR-MVF therapy is a promising alternative treatment for CRPS.

3. Virtual reality-mirror visual feedback therapy for home use

As described in Chapter 2, VR-MVF treatment showed increased analgesic efficacy and benefit in patients with CRPS. However, only a limited number of patients can benefit from this treatment and there are several barriers to performing frequent VR-MVF treatments. First, the VR-MVF equipment is too expensive for individual purchase, so systems are only available in hospitals. Second, using VR-MVF systems requires extensive knowledge of VR and computer systems. The user must be able to set up the system, VR software, and treatment tasks. Third, treatment records, such as the hand and finger movement data and

visual analogue scale evaluations before and after treatment, are hard to obtain without the help of doctors or medical staff. These problems restrict treatment time and frequency. We have been working on two projects to resolve the problems.
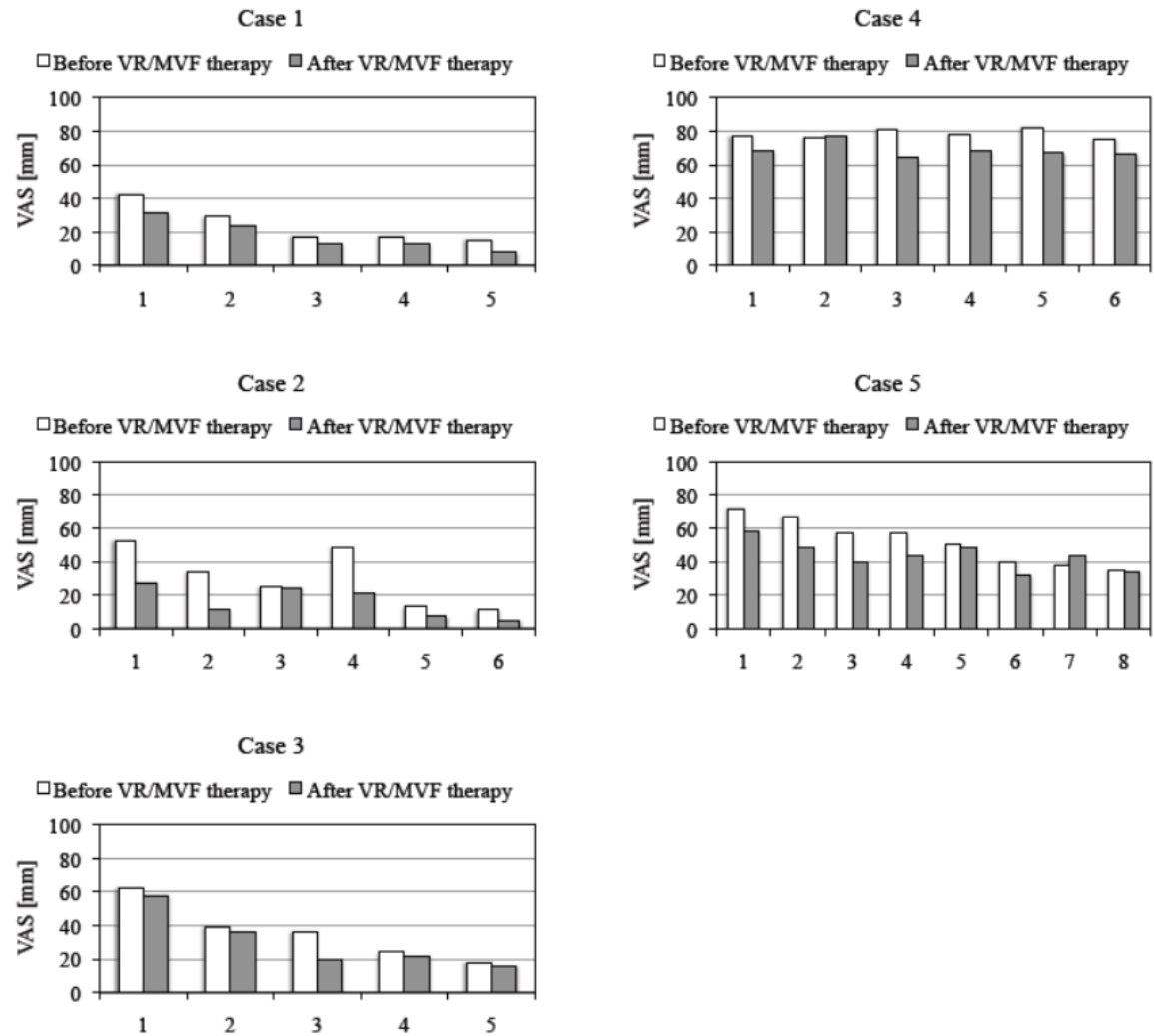

Figure 3. Analgesic effect provided by VR-MVF therapy

A plausible solution for these problems is a remote personal VR-MVF system. This system is composed of an internet-connected personal computer with videophone application software and an inexpensive input device for measuring movements of the non-affected forearm, hand, and fingers. The VE treatment programs are sent through the internet from a server at a hospital. The treatment data, such as pain levels before and after treatment, treatment time, and movement data, are temporarily stored in the personal computer and sent back to the server after treatment sessions. The authors have developed a prototype personal VR-MVF system and plan to expand the prototype to a remote version. This expansion will be accomplished by adding a server and developing data communication and treatment data management software. In a personal VR-MVF system, it is important that the patient be able to observe the virtual hand and forearm movement of the affected side on a display without actually moving the hand and forearm of the affected side. As shown in Figure 4, this system

is composed of a computer with a display, an input device, a web camera with an infrared filter, and processing software for the VE and movement data of the non-affected hand. Another web camera is prepared for videophone communication with a doctor at the hospital. The system measures hand movements and grasping actions on the non-affected side by processing the image data collected by six infrared light-emitting diodes (LEDs) in the input device, as shown in Figure 5. The infrared LED on the palm of the hand detects grasping actions and the infrared LEDs around the hand measure hand location and direction. The system then displays the hand and forearm of the affected side in the VE according to these movement measurements. When the LED in the hand is hidden and the input device receives no infrared light, a grasping motion is detected. A prepared animation of a grasping motion is then played. Conversely, when the infrared light from the LED in the hand is received by the input device, a hand-opening motion is detected. The prepared animation of the grasping motion is then played in reverse. The input device does not measure the motion of each finger. These measurements are not necessary because treatment tasks include grasping an object, moving it, and placing it at a specified position.
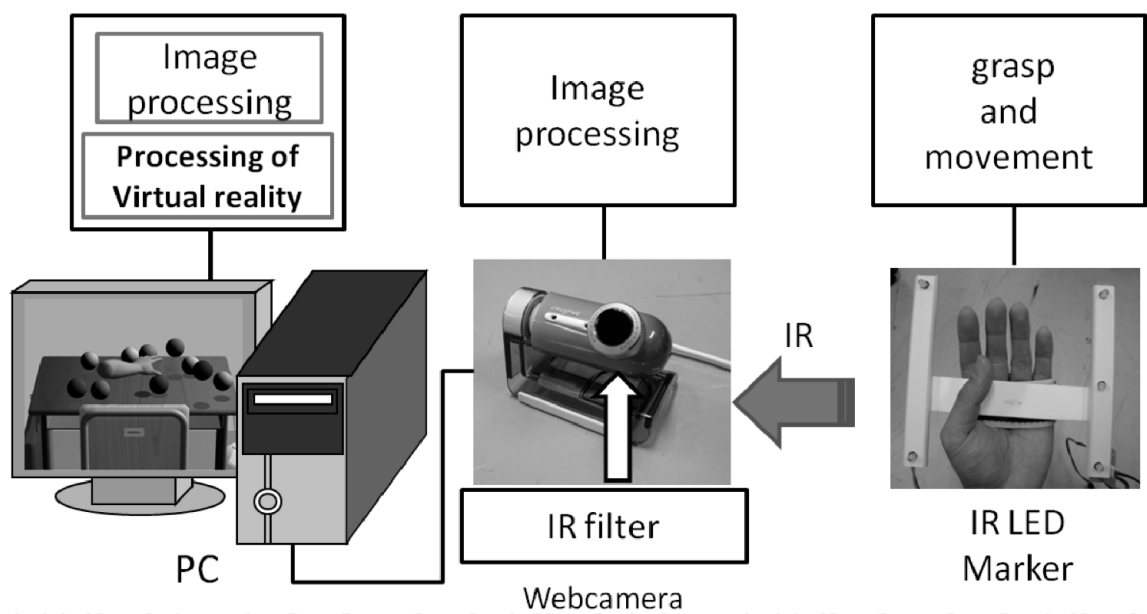

Figure 4. Composition of a personal virtual reality-mirror visual feedback system

Figure 5. Arrangement of infrared light-emitting diodes in the input device

The applicability of the personal VR-MVF system was evaluated by indices of control and realism by the presence questionnaire [42]. The presence questionnaire is a test for measuring the presence of a VE. Each question is related to one or more categories pertaining to control, sensory, realism, and distraction factors of the VE. Each question is evaluated on a scale of fitness from 1 (completely unfit) to 7 (good fit). The control factor measures how easily the user is able to control an object in the VE. The sensory factor measures how well the user perceives the VE. The realism factor measures how authentic the VE feels to the user. The distraction factor measures the user's level of distraction during the session.

Five men and one woman evaluated the system. All subjects were healthy and right-handed, with an average age of 22.6 years. Because sound was not utilized in the original VR-MVF or the personal VR-MVF systems, questions related to auditory stimuli were omitted.
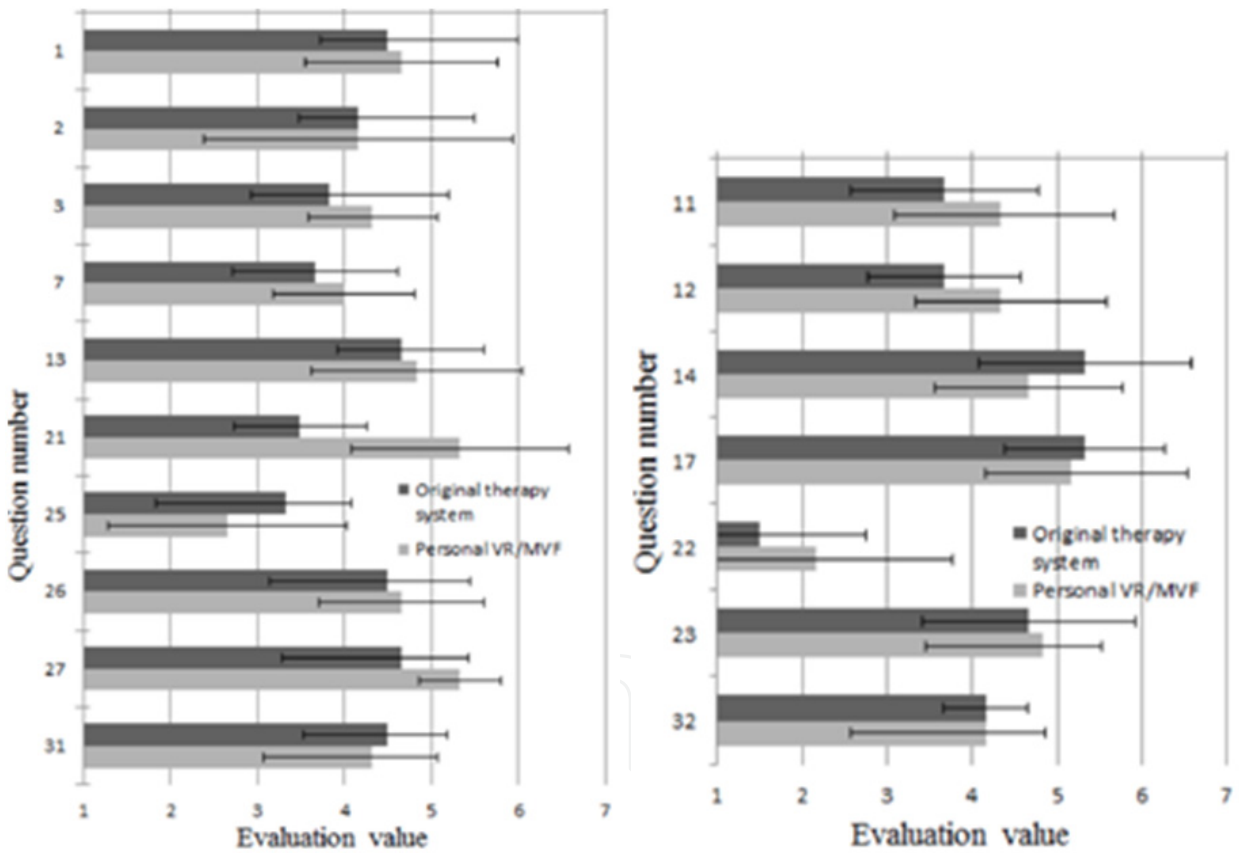

Figure 6. Comparison of presence questionnaire evaluations for the original and personal virtual reality-mirror visual feedback systems (a) Control factor (b) Realism factor

The results of these evaluations are shown in Figure 6. A detailed description of the questionnaire was reported by Witmer [42]. A dark bar indicates the average evaluation of the VR-MVF system and a light bar indicates that of the personal VR-MVF system. The fine lines indicate standard deviations of the evaluation points. For Questions 11 and 25 in Figure 6, lower values indicate better system performance. The personal VR-MVF system

received relatively better evaluations than the original system for the questions related to the control factor and comparable evaluations for the questions related to the realism factor. From these results, the personal VR-MVF system was confirmed to be applicable for patients with chronic pain such as CRPS.

Another approach to VR-MVF for home use is based on the idea of transforming the procedure of VR-MVF into sounds (music) in which data are stored in mobile MP3 players that could then be taken home. Hearing the music reminds the patients of images of VR-MVF that are expected to activate the same brain networks activated during VR-MVF. It is intended to provide some kind of analgesia in patients with chronic pain including CRPS.

4. VR-MVF therapy with sound therapy system

Components of the therapy system

The VR-MVF with a sound therapy system is composed of the following components in a virtual environment: data glove, magnetic sensor, virtual upper limb, several virtual square objects, and a 10×10 matrix of square white switches to turn objects on and off. The object is pressed once and turned on and then pressed again and turned off like a switch of an illumination lamp. When an object is turned on, the white switch changes to blue and signals to emit a sound (Figure 7). To develop this system, we consulted the Yamaha Corporation on the tenori-on [43] because this electronic musical instrument is comparatively easy for the average person who has never played music to perform on. Playing music that a patient prefers contributes largely to therapy; in addition, the patient would continue treatment with enjoyment.

How to perform music

To use a tenori-on, the user pushes buttons with his or her finger. In our system, however, a user does not press buttons with his or her finger to switch the signal, because grasping virtual objects and moving them are important activities in the therapy of CRPS. Therefore, a patient changes the signal by dropping a spherical object onto a switch he or she wants to turn on or off. As with VR-MVF, the objects behave as real objects by means of simple physics simulation, making it easy to create music. Several objects collide and then each object moves in a different direction. As a result, each object presses a button and the user does not need to drop objects on all buttons that he or she wants to switch. When a button is pressed, no sound is emitted, but a point of emission is set. A pressed button emits its defined sound at a constant frequency when a time line is exceeded. The time line represents the frequency of an emission and moves from right to left. The time line is at the right edge in Figure 7. Each button in a single row produces a different sound. Sounds are allocated to each button from back to front in a row. The sound is ranked from lower to higher in a scale of musical notes. Ten rows having the same sounds are put on the virtual table in Figure 7.
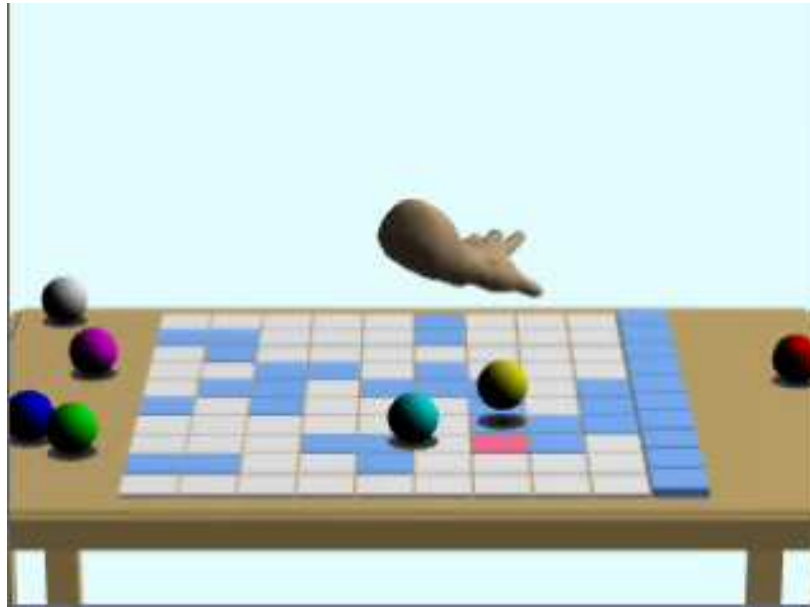
Figure 7. The VR-MVF with a sound therapy system

5. Conclusion

Virtual reality technology has tremendous potential to provide alternative analgesic modalities to patients with chronic pain conditions such as phantom limb pain and CRPS. Virtual reality-mirror visual feedback therapy is a successful example of applying virtual reality technology to pain treatment, especially for patients with chronic pain. In our preliminary study, we showed its beneficial analgesic effects on patients with CRPS. Although VR-MVF is a promising analgesic modality, there are several barriers to VR-MVF becoming a widely used treatment, including its high initial cost. To resolve this problem, we have been working on VR-MVF for home use. Our strategies are intended to provide analgesia for many patients who need an alternative non-invasive analgesic modality.

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