Chapter 13
Virtual Reality

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Abstract This chapter provides an overview on the use of Virtual Reality (VR) in rehabilitation with respect to recent neuroscience and physical therapy reviews of individuals with motor impairments. A wide range of technologies have been employed to provide rehabilitation supported by VR. Several studies have found evidence of the benefits of VR rehabilitation technologies. However, support for their efficacy is still limited due the lack of generalizable results and the uncoordinated effort of many individual, heterogeneous studies that have been conducted. Although VR has clear potential as a rehabilitation tool to improve treatment outcomes, future trials need to take into account the individual perspective of each patient group and consolidate research methodologies across trials to allow for stronger conclusions across the heterogeneous field of neurorehabilitation.

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Interventions must be designed with a strong focus on the patient's needs and clinical outcomes, rather than on the technology available to the clinician.

Keywords Virtual reality · Video games · Game-based rehabilitation · Neurorehabilitation

13.1 Introduction

Effective neuromuscular rehabilitation is crucial for the recovery after traumatic events, such as traumatic brain injury (TBI), spinal cord injury (SCI) and stroke. The world's shifting demographics towards older populations as well as higher prevalence of obesity and health risk factors is expected to lead to an increasing number of cardiovascular diseases and stroke episodes (Population Reference Bureau 2010). Due to advances in medical care, technology, and the ability of stroke units to rapidly provide primary care, there is an increasing rate of stroke and cardiac arrest survivors. Unfortunately, these incidents are rarely without a long-lasting impact on the patient's health. These factors taken together with the rising cost of the world's healthcare systems (Kaiser Family Foundation 2011) support the need for more effective rehabilitation interventions and supportive technologies, such as the use of virtual reality (VR) systems. However, in order to offer patients the best possible therapy it is necessary to analyze and validate the benefits of VR technology as an adjunct or alternative to traditional treatment in the field of neurorehabilitation.

An optimal rehabilitation strategy requires the clinician to select appropriate exercises individually aligned to the needs of the patient, as well as to provide adequate feedback (Dobkin 2004). High numbers of repetitive exercises are commonly part of standard treatments. This requires the patient to perform additional exercises at home without the supervision of the therapist, which further complicates the sustained quality and adherence to the treatment program. Repetitive exercises without therapist supervision, and therefore no feedback, can lead to lack of motivation causing the patient to poorly perform the rehabilitation routine in quality and quantity. Additionally, the therapist can only rely on the patient's verbal report on frequency and quality of the exercises performed, which hinders the ability of the therapist to adequately adjust the rehabilitation routine. These factors arguably lead to poorer rehabilitation outcomes and could even cause further injuries. Hence, the monitoring of quality and quantity of home-based rehabilitation interventions can potentially have a large positive impact on the quality and adherence to long-term treatments and rehabilitation outcomes.

Recent advances of video game technology and VR systems have led to an increasing use of these systems for rehabilitation purposes. Henderson et al. (2007) define VR as a "computer based, interactive, multi-sensory environment that occurs in real time". Bohil et al. (2011) state that "VR system components work in concert to create sensory illusions that produce a more or less believable simulation of reality". An additional VR definition by Weiss et al. (2004) states:

> Virtual reality typically refers to the use of interactive simulations created with computer hardware and software to present users with opportunities to engage in environments that appear to be and feel similar to real-world objects and events (Weiss et al. 2004).

VR technology has been a widely applied rehabilitation tool, addressing many different disorders and therapeutic needs. In this chapter, we will limit our discussion to the use of VR as a therapeutic tool to regain or improve physical function after neurological injury.

This chapter provides an overview of the use of VR technology in rehabilitation with respect to recent reviews on neuroscience and stroke research (Bohil et al. 2011; Henderson et al. 2007; Laver et al. 2011) and motor impairments (Holden 2005; Sveistrup 2004), with a specific focus on physical rehabilitation. This work differs from previous reviews by focusing on how technology and rehabilitation needs alignment, especially in neuromuscular rehabilitation.

13.2 Virtual Reality Technologies in Rehabilitation

This section provides a general basis for understanding VR as a technology and its potential application in rehabilitation.

Depending on input and display devices, VR systems can be divided into fully immersive and non-immersive setups. The advantage of fully immersive systems is the user's strong "sense of presence" which has been attributed to the convergence of the system's multisensory input (Henderson et al. 2007). In non-immersive systems, the VR system often consists of a computer monitor, mouse, keyboard and possibly joysticks, haptic devices and force sensors. The multi-sensory illusion of actually being in the virtual environment can motivate patients to continue training over multiple therapy sessions.

VR systems are often comprised of a multitude of technologies, software and hardware devices. Most of these devices are unfamiliar to patients and therapists. Hence, the fields of human–machine-interaction/human–computer-interaction are of critical importance to the use of VR technology in rehabilitation settings. The most prevalent sensory stimulations in VR systems are found in visual, auditory and haptic (tactile) modalities (Bohil et al. 2011). Visual feedback is traditionally provided by computer screens, large screen projection, wall projectors ("CAVEs"—Cave Automatic Virtual Environments, where the virtual environment is projected on a concave surface), and head-mounted displays (HMDs). HMDs are head-worn display units consisting of one small display for each eye, earphones and often a head-tracking unit. Acoustic feedback in mono or stereo sound can be provided by speakers, headphones or other more sophisticated surround sound systems. Haptic feedback is less common but extremely important for specific applications. It can be provided by robotic actuators or haptic gloves that vibrate against the skin or within the device.

Fig. 13.1 Virtual hand controlled by an amputee via pattern recognition of myoelectric signals

Input devices are important for each VR system to provide the user with intuitive ways to control events within virtual environments. Examples of commercial devices include standard PC peripherals such as: keyboard, mouse and joystick; posture platforms; marker-based motion capturing and tracking systems (e.g. OptiTrack), infrared light (e.g. Microsoft Kinect, ARTTRACK3), instrumented gloves (e.g. AcceleGlove and CyberGlove) and inertia trackers in hand-held devices (e.g. accelerometer/gyroscopes in smart phones or the Nintendo Wii); and more recently, brain-computer interfaces (BCIs) that detect electroencephalography patterns of the user (e.g. Emotiv Epoc). On the research side, the prediction of motion intent based on patterns of myoelectric activity is also used as input for VR systems (Ortiz-Catalan et al. 2013). Figure 13.1 shows a trans-humeral amputee controlling a virtual hand through pattern recognition of the myoelectric activity recorded on the surface of the subject's stump (Fig. 13.1).

VR software solutions require a complex integration of virtual environments (VEs) and the previously discussed VR hardware. Several development frameworks are available in order to create complete VR solutions. These frameworks include game engines such as Unity, Gamebryo, CryEngine, UNiGiNE, Ogre3D and Unreal Engine as well as simulation and VR engines such as Quest3D and WorldViz Vizard. Only the latter already provide the capability to interface with a wide range of trackers and input devices. Regardless of the development platform developers need to be aware of the specific requirements of the target population and provide clinicians and patients with appropriate performance feedback and options to tailor the application towards the individual needs of each patient. Traditional off-the-shelf games often do not provide such options and lack the customizability that is needed to address individual rehabilitation needs (Lange et al. 2010).

Middleware such as the Flexible Action and Articulated Skeleton Toolkit (FAAST) (Lange et al. 2011b) and MiddleVR can be utilized to seamlessly integrate VR hardware into existing and newly developed games. FAAST is a depth-sensing framework that enables clinicians to use full-body tracking with the Microsoft Kinect to play off-the-shelf computer games. Gestures can be customized to fit the needs of each individual user. MiddleVR is a sophisticated VR

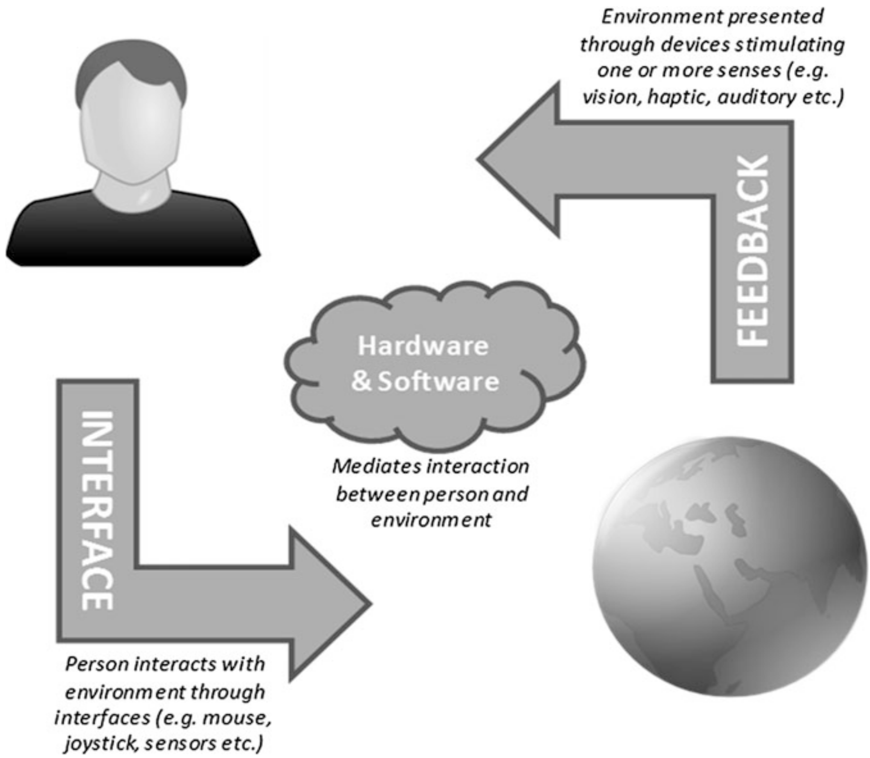

Fig. 13.2 Illustration of the role of VR as a therapeutic tool in neurorehabilitation

toolkit that enables developers to immerse users by implementing VR input and output devices as part of the user experience.

Despite the wide range of available VR software and hardware the user still has to take a central role in the virtual rehabilitation ecosystem. Specifically, the needs of clinicians and patients have to be addressed in order to create rehabilitation tools that provide additional benefits beyond traditional therapy. Instead of interacting with the real world, users interact with VEs in order to train skills as part of their rehabilitation routine. Interfaces and feedback are essential for a VR system to connect the user with the VE (Fig. 13.2).

Each patient has individual strengths, weaknesses and therapy goals and each clinical setting has different requirements for documentation, safety and therapy protocols. Only when user interfaces and feedback mediated through VR software and hardware accommodate these individual user goals, VR technology can have a positive impact on neurorehabilitation (Fig. 13.2).

By example of a VR driving application, the role of each of Fig. 13.2's elements becomes apparent. Exemplarily, the user can interact with the VE by using a joystick, steering wheel, pedals, gears or even gestural input (user interface) to control a car on a computer screen (visual feedback). Additional feedback can be provided by adding various car-related sounds, tactile information (e.g. force feedback for the steering wheel) and visual information (e.g. additional screens for side windows and mirrors). Further hardware elements such as motion platforms can be added to increase realism of the VR simulation system. The software is needed to translate the user input into events and actions within the VE (e.g. steering changes the path of the car). Further, the software is responsible for providing task content of appropriate difficulty level (e.g. different locations and traffic conditions) and giving feedback based on the user's performance (e.g. providing scores and reports).

Recent advances in game development technology and the availability of low-cost tracking devices have greatly enhanced the capabilities of interfaces, VR hardware and software to connect the user with a meaningful VE for therapy. However, clinicians and developers need to work together to assure that feedback and task content within the VE are tailored towards the user's individual needs. Mainstream VR systems for neurorehabilitation will only become a reality when all elements of a therapeutic system are adaptable to the user's specific goals while still being affordable for widespread use in clinics and patient homes.

The remainder of this chapter will discuss how previous studies have utilized and evaluated clinical VR systems and what we can learn from these existing results in order to better address the needs of patients in neurorehabilitation.

13.2.1 Literature Summary

Despite recent technological advances that make VR systems more appealing to clinical practice, there is still a considerable lack of scientific evidence of how VR systems can be meaningfully implemented in existing rehabilitation routines. There is some evidence that VR training for surgical skills has shown transfer to real work activity (Gurusamy et al. 2008, 2009; Torkington et al. 2001). However, there is limited evidence of the same kind of transfer for VR-based functional motor tasks (Holden 2005). Furthermore, there is little consensus in the literature about how VR technologies can be utilized in the clinical setting and how efficacy can be demonstrated across patient populations.

A number of recent reviews have been published on the use of VR and video games for physical rehabilitation after a stroke. VR systems in rehabilitation of both upper and lower limbs were evaluated in the Veterans Affairs/Department Of Defense (VA/DoD) clinical practice guidelines for the management of stroke rehabilitation (2010). The VA/DoD working group came to the conclusion that VR systems are recommended for upper and lower limb rehabilitation after stroke. This conclusion was based on studies by Kim et al. (2009), Yang et al. (2007), Mirelman et al. (2009) and Jaffe et al. (2004). According to these studies, chronic hemiparetic patients with stroke showed significantly greater improvement in the Berg Balance Scale, gait velocity, cadence, step time, step length, and stride length when they receive an additional 30 min of VR therapy each session compared to the control group (Kim et al. 2009). Post stroke patients who received VR-based treadmill training maintained a significantly faster community walking speed (Yang et al. 2007). Patients using a robot with a VE showed improvements in gait velocity, distance, and community ambulation compared to the control group using a robot without VE (Mirelman et al. 2009). Significant improvements in gait velocity of patients with virtual versus real stepping paradigms were reported by Jaffe et al. (2004).

No recommendation for or against the use of VR systems was given in a systematic review of upper limb rehabilitation by Henderson et al. (2007). The authors evaluated existing scientific evidence for the effectiveness of VR in upper extremity stroke rehabilitation. They included six studies in their review and examined the effects of immersive and non-immersive VR compared to conventional therapy or no therapy in hemiplegic stroke survivors. They concluded that current evidence on the effectiveness of VR rehabilitation for upper extremities in patients with stroke is limited, but sufficiently encouraging to justify additional clinical trials in this population.

Miller et al. (2010) conducted a literature review to determine the effectiveness of VR interventions for motor rehabilitation in stroke victims and found that there is evidence that using VR systems for motor rehabilitation is beneficial. However, all six reviewed studies reported small sample sizes in mostly uncontrolled trials, using high-cost VR interventions that mostly targeted upper extremities. Therefore, additional controlled investigations are needed to determine whether VR interventions are more beneficial than standard therapy protocols and whether costly VR systems are needed.

In a review by Holden (2005) VR interventions for motor deficits in stroke, acquired brain injury and Parkinson's disease were assessed. The author summarized the utility of VR applications in four major findings: (1) people with disabilities appear capable of motor learning within VEs; (2) movements learned in VR by people with disabilities transfer to equivalent real world tasks in most cases, in some cases even generalizing to other untrained tasks; (3) all of the few studies that have compared motor learning in real and virtual environments found some advantage for VR training; and (4) no occurrences of cyber sickness in impaired populations have been reported to date in experiments where VR has been used to train motor abilities.

Sveistrup (2004) published a review on VR technologies specifically applied to motor rehabilitation. The reviewed studies conclude that VR technology allows therapy to be provided within a functional, purposeful and motivating context. Adaptation of task difficulty level to the subject's skills was identified as an important factor to engage the patient in a repetitive exercise program and to prevent boredom and fatigue during therapy. The author cites studies from a wide range of different clinical domains, each showing the potential of VR technology. However, high costs of VR systems and lack of compelling evidence for the efficacy of VR interventions across different domains of motor rehabilitation require a strong focus on further validation and development of low-cost hardware and software.

More recently, Bohil et al. (2011) reviewed the use of VR applications in several clinical domains including psychiatry, neurorehabilitation and pain treatment. The authors specifically discuss the concepts of presence and immersion as “the physiological product of technological immersion” and “the sense of being there”. Even though the reviewed studies did not specifically address neuromuscular rehabilitation, parallels regarding the users’ needs and the applied solutions can be drawn between rehabilitation disciplines. For instance, VR has been shown to be effective in engaging the sensorimotor system and providing means to monitor small changes in user performance.

Bohil et al. (2011) further discuss VR applications in two areas of neurorehabilitation: balance disorders and functional recovery after stroke. In this context the authors review two articles of August et al. (2006) and Adamovich et al. (2009) in which evidence is shown that VR interventions help to engage primary and secondary motor areas related to recovery of muscle control after stroke. Bohil et al. (2011) also review the findings of Baram and Lenger (2009) and Baram and Miller (2006) who concluded that VR systems can provide feedback through multimodal stimulation that helps engaging in reflexive responses and bypassing damaged brain areas. Similar promise was shown with using VR technology for hand rehabilitation. The authors cite Henderson et al. (2007) and Merians et al. (2002) whose patients showed significant improvements in the movement, use and control of their hands relative to baseline and to other rehabilitation approaches after performing VR exercises with visual, auditory or haptic feedback. The studies of Merians et al. (2006) and Adamovich et al. (2009) were reviewed for their use of force-feedback data gloves to interact with VEs. The authors report improvements of the patients’ individual finger control, thumb and finger range of motion, and thumb and finger speed. The promise of VR technology has been shown across a wide range of domains of neurorehabilitation and Bohil et al. (2011) conclude that with increasing quality, higher immersion and presence of VR systems, barriers for adoption in research and clinical practice are likely to be overcome.

Laver et al. (2011) conducted a Cochrane Review to evaluate the effects of VR and interactive video gaming on upper limb, lower limb, and global motor function after stroke. Nineteen trials were included in this review, allowing the authors to collate results and identify medium effect sizes on recovery of arm function and activities of daily living. However, individual studies are very heterogeneous and too small to gain deeper insights into the exact mechanisms that make VR systems successful for the recovery of motor function. The authors further conclude that recent advances in VR technology and increasing research activity in the field of virtual rehabilitation are promising. Reports of adverse side effects such as motion sickness and nausea have been rare, so that larger randomized controlled clinical trials that compare VR therapy to standard interventions are justified and needed to advance the field of VR neurorehabilitation further.

13.2.2 Advantages of VR Rehabilitation

Based on the previous review of the VR rehabilitation literature, several important strengths of VR rehabilitation have been identified. These strengths have to be considered carefully to evaluate whether using a VR application provides any benefit over traditional therapy. The key question then becomes: why not just practice the real-world functional task instead of using expensive hardware and software? In order to answer this question, the following discussion on the advantages of VR rehabilitation applications is focused on a few important aspects relevant to motor learning. Motor rehabilitation should be focused on functional movements in a relevant environment with high intensity, a large number of repetitions and appropriate feedback (Timmermans et al. 2009). Repetition is important to promote motor learning and cortical plasticity. The learning process must be reinforced by feedback which links the patient's performance to a successful task outcome. Lastly, motivation is needed to repetitively carry these tasks out over an extended period of time. VR technology is believed to provide all of these critical components to provide an engaging and relevant task environment that can be tailored to the needs of the patient (Henderson et al. 2007).

13.2.2.1 Individualized, Task-Specific Training

It is well known that task-specific practice is needed for motor learning to occur. Butefisch et al. (1995) demonstrated that short, repetitive, task-specific training (15 min/day, 2 times/day) is sufficient to improve strength and function of the affected hand in stroke patients. By designing VEs that look like the real world and also incorporate challenges that require real world functional behaviors, motor functions for everyday tasks can be selectively trained. However, task specificity on its own is not sufficient to provide adequate therapy content. The concept of client-centered rehabilitation and individualized therapy goals have become a central aspect of modern neurorehabilitation. Clinicians are encouraged and expected to focus on the strengths, weaknesses and individual circumstances of each patient in order to restore a person's participation in daily life (World Health Organization 2001; Ylvisaker 2003). These circumstances also include the patient's social environment like family members and friends who should be integrated in the long-term planning of a rehabilitation strategy. VR applications can provide the means to safely expose the patient to realistic and functional training environments which can be tailored to the individual's level of ability (Koenig et al. 2011; Koenig 2012). Supervising therapists can precisely manipulate and control task complexity and intensity while the patient is still following a therapy plan at an inpatient or outpatient setting. Once a patient is discharged from the clinical setting friends, family and the patients themselves are often on their own to continue an exercise regime. In these situations online tools, telerehabilitation tools and affordable VR systems can greatly enhance long-term outcomes by motivating the patient to adhere to a therapy plan without constant supervision by clinicians. However, these home-based and client-centered scenarios have to be considered and explored by researchers and VR developers alike in order to provide VR systems that are affordable, user-friendly and motivating. Consequently, all involved stakeholders (i.e. patients, clinicians, researchers, patients' families) should be actively involved in the VR development and research processes (Koenig et al. 2012).

User interfaces can play an important role in making VR applications more user-friendly and motivating. Until recently, game interfaces were limited to a computer mouse, arrow keys on a keyboard, or a joystick. Recent advances in video game technology have revealed more low-cost devices that can sense the user's motion. Exemplarily, the Microsoft Kinect can sense the full-body pose for multiple users without the use of markers or handheld devices. The Kinect sensor and several similar devices which were originally designed for recreation are now being adapted by clinicians for therapeutic purposes (Lange et al. 2011a). Several tools are available to design custom body postures and gestures for playing off-the-shelf games. The Flexible Action and Articulated Skeleton Toolkit (FAAST) (Lange et al. 2011a, b) allows clinicians to specify gestures that are customized for each patient. This allows individuals with different levels of abilities to play the same game as part of their rehabilitation or simply for recreation. In addition to such off-the-shelf use of video game technology, interactive (serious) games can also be specifically designed for rehabilitation (Lange et al. 2011a).

13.2.2.2 Motivation

VR offers a realistic, safe and motivational setting in which complex activities can be practiced. However, the user can also be provided with a sense of achievement, even if he/she cannot perform that task in the 'real world'. In an overview of VR technology by Rizzo and Kim (2005) motivating game factors are described as one of the major advantages of VR systems, especially as part of clinical assessments. When patients are engaged in gaming tasks, attention is drawn away from the fact that an assessment is taking place, thus providing a more accurate estimate of naturalistic capability. Further evidence suggests that when a user concentrates on the game rather than their impairment, exercises becomes more enjoyable, motivating and more likely to be maintained over the many trials needed to induce plastic changes in the nervous system. For example, Harris and Reid (2005) observed children with cerebral palsy playing VR games. Motivational factors for each game were analyzed and discussed. Variability of content, being challenged with an appropriate level of difficulty and competing against others appeared to be the most relevant motivational factors of the tested VR games. Motivation was also important in a study of King et al. (2010), who investigated augmented reality computer games which provided rewarding, goal-directed tasks for upper limb rehabilitation via a gravity supported reaching task. Motivational factors for exercising with the system included intellectual stimulation, feedback (e.g. game scores), physical benefits from exercising, social play with peers, appropriate levels of difficulty and the ability to relate to the game.

13.2.2.3 Feedback

Feedback can be very important for the user's motivation. The user always needs to know when and why a task was completed (un-)successfully in order to promote (errorless) learning and prevent frustration. Feedback can be given as absolute (correct/incorrect) or graded information (error scores, deviation from optimum) and in different modalities. Most computer applications and VR systems present the user with visual and auditory information. For VR systems, this can encompass stereo speakers and PC monitors on the lower end of the cost spectrum as well as projection screens, head-mounted displays and surround sound systems as more costly alternatives. An example of a traditional VR system is the Vivid Group's Gesture Xtreme VR system by Kizony et al. (2003), which has been used for neurological rehabilitation. The user stands or is seated in front of a large video screen and a speaker system to provide multimodal input for functional motor rehabilitation tasks.

More recently, tactile user feedback has been introduced to VR systems. Haptic feedback devices include gloves, joysticks and exoskeletons that simulate the feel of forces, surfaces and textures as users interact with virtual objects. For example, the Cybergrasp system is a force-reflecting exoskeleton that can apply forces of various temporal profiles to allow individual finger movements. The system has shown to be a safe and feasible device for the training of hand function with hemiparetic patients (Adamovich et al. 2009; Merians et al. 2011).

13.2.3 Disadvantages of VR Rehabilitation

Over the past 20 years several threats and disadvantages to VR technology have been reported in the literature. Rizzo and Kim (2005) summarized several potential threats and weaknesses that could prevent widespread adoption of VR applications in a comprehensive SWOT analysis. One of the main disadvantages of VR as a viable rehabilitation solution is the lack of standards, frameworks and compatibility amongst the many different available technologies. Drivers, operating systems, hardware, databases and the actual VR content all have to be compatible and operate on a range of different system configurations. In addition, adverse side effects, lack of cost-benefit analyses and the fear of clinicians that they will be replaced by VR applications have been brought up as potential barriers to the use of this technology. Some studies reported transient side effects after using VR such as dizziness, headache (Crosbie et al. 2012) and pain (Sucar et al. 2009). Simulation/cyber sickness can be a serious concern for the widespread adoption of VR in clinical settings as the systems need to be used with brain-injured users over extended periods of time (Bohil et al. 2011). However, reports of cyber sickness incidents have been mixed, as Holden's review (2005) reports no occurrences of adverse side effects in experiments where VR has been used to train motor abilities.

In addition, high cost has always had a negative impact on the widespread use of VR rehabilitation tools. Even though the cost of displays and PC hardware has been rapidly decreasing over the past years, fully immersive systems are still expensive. Especially complex projection screens (e.g. CAVE systems or projection domes) and wide-field-of-view HMDs are not affordable for everyday clinical use. On the contrary, handheld devices and gaming peripherals such as the Microsoft Kinect, Nintendo Wii, Razer Hydra and PlayStation Move have provided access to low-cost tracking interfaces which make VR experiences accessible to a large audience.

Lastly, legal aspects of VR use in neurorehabilitation have to be considered. According to the Medical Device Directive (2007) a medical device is defined "a*s any instrument, apparatus, appliance, software, material or other article, whether used alone or in combination, including the software intended by its manufacturer to be used specifically for diagnostic and/or therapeutic purpose"* (Medical Device Directive 2007, p. 5). If systems are used for rehabilitation purposes, they are per definition medical devices and have to be certified accordingly. This could potentially increase the costs of using these products, and has to be considered as one of the potential risks using VR systems in neurorehabilitation.

13.2.4 Application to Neurorehabilitation

Rehabilitation is a complex and *"active process by which those affected by injury or disease achieve a full recovery or, if a full recovery is not possible, realize their optimal physical, mental and social potential and are integrated into their most appropriate environment."* (World Health Organization 2001). Rehabilitation includes a wide range of activities and services aimed at reducing the impact of injuries and disabilities by applying coordinated problem-solving processes across many disciplines. Many patients attending rehabilitation services have multi-factorial, complex problems that often require several interventions to be given by different health care professionals. It is unlikely that VR interventions will be appropriate in all cases as a sole one-size-fits-all solution. At this point it is difficult for clinicians to choose an appropriate VR intervention from the large number of available technologies. While the previously discussed reviews give an overview of available interventions and VR systems, most systems are in prototypical stages and have only been employed in preliminary trials or laboratory settings. Comprehensive comparisons of usability and efficacy across all interventions for motor rehabilitation are still lacking.

When choosing a VR task for neurorehabilitation, clinicians should consider the difficulty level (Can I challenge the patient appropriately throughout the rehabilitation process?), task complexity (Can the task be broken down into individual components?), task content (Is the task relevant and motivating for the patient?), available feedback (Is the feedback direct and understandable for the patient?) and the potential for transfer of skills (Can the task content be gradually changed to promote transfer to real life?).

Moreover, it should be considered whether each intervention is grounded in a model of health and disability like the International Classification of Functioning, Disability and Health (ICF)(World Health Organization 2001). It is important to work with such models when developing or applying VR tools in order to standardize and classify interventions from a clinical perspective regardless of software and hardware components. For example, it is possible to design a VR intervention that solely focuses on basic body functions (e.g. balance using the WiiFit Balance Board) in which the user is only asked to shift balance according to some basic instructions. This same application can also target the ICF level of activities by integrating the balance task as part of a snowboarding or similar balance game. Lastly, VR interventions also can target the level of participation by placing a functional task (e.g. balance training) in a relevant context such as shopping, cooking or other activities that are essential for each individual to participate in daily life.

13.3 Conclusion and Future Challenges

The findings of the reviews discussed in this chapter suggest that the application of VR in rehabilitation seems promising. However, the studies so far are too few and too small to draw strong conclusions. The advantages of motivation, task relevance, structured feedback and tailored tasks with appropriate difficulty level have been described as advantages of VR by nearly all authors. Pricing and availability of VR hardware, software and gaming peripherals such as the Microsoft Kinect, Nintendo Wii and PlayStation Move have seen much improvement over the past years. However, expensive one-off VR systems still exist and compatibility of different hardware, software, drivers and development protocols is still a problem. Furthermore, consistent evidence for the usability and efficacy of VR interventions across clinical domains does not exist yet. Clinical trials are sparse, uncontrolled, of small sample sizes and lack consistent methodology across trials and VR systems. The development of clinical, methodological and technical standards is needed before VR interventions can become a widespread alternative to traditional therapies.

Through the review of the existing literature and state of the art in VR technology, one is left with several key questions which are of high relevance to the use of VR interventions in neurorehabilitation:

- There are many differences between a realistic, functional VR task and its real-world counterpart. Which aspects of the VR task contribute to its success?

Which are key elements that help users engage with and benefit from the rehabilitation task?
- VR technology can be intimidating and overwhelming for some users. Which patients and therapists can benefit most from VR interventions? Which patient characteristics, motor and cognitive deficits are best suited for VR rehabilitation protocols? Are there cases in which VR interventions can be detrimental to rehabilitation progress?
- Which training tasks, gaming aspects, hardware and user feedback are the most immersive? How can motivation to exercise be maintained over extended periods of time?
- At which point throughout the rehabilitation process should VR interventions be applied? Are different applications required for acute, sub-acute and chronic disorders?
- How can the use of VR technology in neurorehabilitation be justified with cost-benefit analyzes?

Based on the previous reviews and key questions, the following challenges and goals are expected to be of particular value to the VR neurorehabilitation field:

- Cost-effective hardware was one of the main barriers that prevented VR from becoming a mainstream technology over the past 20 years. However, tracking devices and HMDs are finally evolving towards high-quality affordable products. The goal should be for VR systems to not only be affordable by a clinic, but also for the patient to continue rehabilitation after being discharged from the inpatient or outpatient program.
- Naturalistic user interfaces are starting to emerge in the form of gaming peripherals. The current generation of these devices already provides great opportunities for clinicians and researchers to integrate full-body tracking into rehabilitation applications and games. In the future, these devices need to accurately and reliably detect the full human body including face, fingers and voice at a level that is currently reserved to prohibitively expensive research-grade tracking systems.
- The answer to most of the previously stated key questions lies in a series of sufficiently-powered randomized controlled trials. These trials need to validate a set of the most promising VR interventions across several patient populations. Replication of studies is also needed.
- The VRPN peripheral standard has already set an example of how VR devices can work together. However, more industry standards for device drivers, VR hardware, software and the VR development and validation process are needed.

VR technology is a promising tool in the clinician's and researcher's toolkit. With a coordinated effort between VR developers, engineers, clinicians and researchers, VR interventions have the potential to provide a safe, customized and motivating rehabilitation experience to patients across all spectrums of neurological injury.

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