Virtual Rehabilitation

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Abstract This chapter addresses the current state of the art of virtual rehabilitation by summarizing recent research results that focus on the assessment and remediation of motor impairments using virtual rehabilitation technology. Moreover, strengths and weaknesses of the virtual rehabilitation approach and its technical and clinical implications will be discussed. This overview is an update and extension of a previous virtual rehabilitation chapter with a similar focus. Despite tremendous advancements in virtual reality hardware in the past few years, clinical evidence for the efficacy of virtual rehabilitation methods is still sparse. All recent meta-analyses agree that the potential of virtual reality systems for motor rehabilitation in stroke and traumatic brain injury populations is evident, but that larger clinical trials are needed that address the contribution of individual aspects of virtual rehabilitation systems on different patient populations in acute and chronic stages of neurorehabilitation.

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J.L. Pons et al. (eds.), *Emerging Therapies in Neurorehabilitation II*,
Biosystems & Biorobotics 10, DOI 10.1007/978-3-319-24901-8_12

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

1 Introduction

The world population is expected to grow to 9.68 billion people by 2050 [25]. More importantly, the proportion of people aged 60 or older is expected to increase in the so-called "more developed countries" from currently 23 to 32 % of the total population by 2050 [32]. With neurological disorders such as stroke, Parkinson's disease, or multiple sclerosis being more prevalent in older adults [1, 8, 30], our healthcare systems desperately need cost-efficient, widely available interventions that can address the cognitive and motor impairments of the aforementioned disorders and help reintegrate affected individuals in society.

Virtual rehabilitation technologies and interactive off-the-shelf games have seen increasing popularity in clinical settings over the past two decades [10, 14]. Virtual rehabilitation includes a wide array of applications that use virtual scenarios and environments for the purpose of clinical assessment and remediation. Available systems range from complex motion platforms, projection systems, tracking systems, and head-mounted displays to low-cost gaming consoles and motion-tracking sensors. Distinguishing factors of such systems are the use of fully virtual environments (i.e., virtual reality), real environments with an overlay of virtual information (i.e., augmented reality), or a mixture of both (i.e., mixed reality). Further, virtual rehabilitation setups can be immersive or non-immersive where immersive denotes systems in which three-dimensional scenarios are displayed and the user can change visual perspective through head movements (e.g., head-mounted displays or cave projection setups). On the contrary, non-immersive systems present virtual scenarios on a two-dimensional display (e.g., on a TV, laptop, or computer screen) with or without interface devices such as keyboard, computer mouse, or a joystick. Regardless of the actual hardware and software configuration, these approaches are often considered viable alternative or adjunct treatments to existing therapies, because of their motivational nature and precise control over feedback and task parameters.

This chapter focuses on the use of virtual rehabilitation systems for the treatment of motor deficits after stroke and traumatic brain injury. Recent advances of virtual reality hardware are being discussed and their potential for new rehabilitation systems along with strengths and weakness are being outlined. Moreover, relevant clinical trials and meta-analyses since the writing of the previous version of this chapter are summarized and their results discussed.

2 Advances in Virtual Reality Technology

Virtual reality systems are often a heterogeneous set of input/output devices that can consist of a wide range of displays, tracking devices, controllers, and computer systems. Historically, such systems were almost exclusively associated with high costs, cumbersome, wired equipment, and a lack of compatibility between different devices and device drivers [27]. However, within the past two years virtual reality technology has seen a transformation toward low-cost components that are being developed and marketed for the rapidly growing video and computer game industry. Much of that growth is also driven by the rise of mobile computing and the availability of high-resolution mobile displays. Modern head-mounted displays have evolved from cumbersome, tethered devices to goggles that simply allow the user to attach an off-the-shelf smartphone and leverage the inbuilt motion sensors and cameras of the phone. Consequently, prices for head-mounted displays have dropped from tens of thousands to merely hundreds of dollars while image quality and tracking latency have improved tremendously. Examples of such new display solutions are the Oculus Rift,[1] Samsung Gear VR,[2] Avegant Glyph,[3] Durovis Dive,[4] Google Cardboard,[5], or the Zeiss VR One.[6] Most of these are still in alpha or beta prototype stage, but new innovative products are announced on a regular basis and should invigorate the competition further. A similar trend is evident for video game peripherals and 3D interaction devices which are mostly developed for console and computer game markets. New tracking devices such as the Microsoft Kinect 1 and 2,[7] Leap Motion controller,[8] Razer Hydra,[9] Nimble Sense[10], and treadmills such as the Virtuix Omni[11] and Cyberith Virtualizer[12] provide an affordable entry to naturalistic 3D interaction in virtual scenarios. All of these new competitors are of high importance to developers and researchers in the virtual rehabilitation field, as for the first time in the history of virtual reality technology, therapeutic systems have become affordable and accessible for use in the wider clinical setting, outside of the research laboratory. In addition, the development of virtual rehabilitation software has become much more accessible

[1] https://www.oculusvr.com
[2] http://www.samsung.com/gearvr/
[3] https://www.avegant.com
[4] https://www.durovis.com
[5] https://www.cardboard.withgoogle.com
[6] https://www.zeissvrone.tumblr.com
[7] http://www.microsoft.com/en-us/kinectforwindows/develop/
[8] https://www.leapmotion.com/
[9] http://www.sixense.com/razerhydra
[10] http://www.nimblevr.com/
[11] http://www.virtuix.com/
[12] http://www.cyberith.com/

as game engines such as Unity,[13] Unreal Engine 4[14], and CryEngine 3[15] are widely available for low monthly subscriptions or even for free. Each development tool comes with large communities of enthusiastic game developers who provide free assets, tutorials, and help on online forums and discussion groups. Virtual reality hardware companies have realized the potential of these large communities and provide free integrations of their devices and drivers for the most common game engines. All of these factors taken together provide an excellent ecosystem for the development of low-cost virtual rehabilitation systems that would have cost hundreds of thousands of dollars three to five years ago.

3 Advantages of Virtual Rehabilitation

Innovative technologies such as virtual rehabilitation tools are being applied by using motor learning principles and taking advantage of neuroplasticity in order to compensate, restore, and recover loss of sensorimotor function occurring in stroke and traumatic brain injury patients. This section will outline the different factors that make virtual rehabilitation systems a suitable option for the treatment of sensorimotor deficits in neurorehabilitation and add value beyond traditional forms of treatment.

(a) Comprehensive data collection

Data is at the core of most other aspects of virtual rehabilitation systems mentioned in this section. Comprehensive collection of performance data enables the patient and therapist to track rehabilitation progress and adjust training parameters for optimal recovery. Performance data is also necessary to track the efficacy of each rehabilitation system and can help the clinician decide which intervention is best used for different patient populations or individual patients. Data collection can encompass usage patterns, task completions, task difficulty adaptations, and task outcomes on a macro level and reaction times, responses to task stimuli, movement quality, and logging of feedback or distractions on a micro (behavioral) level. Furthermore, each variable can be tracked and summarized over longer timespans across multiple sessions or even across patients and patient populations. This allows researchers and clinicians to track the efficacy of combinations of tasks and feedback for patients with different deficits, lesion locations, and demographics. Moreover, summary data of task usage gives deeper insights into the success and habits of clinicians and how their experience or background influence therapy outcomes with virtual rehabilitation tools.

Large datasets can be collected when using sensors and motion tracking systems. Oftentimes, datasets can be too complex for unprocessed use by clinicians and must be condensed before they can aid clinicians in their decision-making

[13] http://www.unity3d.com/

[14] https://www.unrealengine.com/

[15] http://www.cryengine.com/

process. Compared to clinical observation using rating scales, automated data collection of virtual rehabilitation systems can capture many high-resolution variables simultaneously. Exemplarily, a tracking system can capture movement of all tracked joints at millisecond and millimeter accuracy and combine this information with the system's presentation of task stimuli, distractions, and the user's responses and errors. Manually observing the same scenario and assessing all variables in a reliable and valid manner is simply impossible. Additionally, automating data collection frees the therapist's resources and allows for unhindered interaction between patient and therapist.

(b) Multisensory feedback

Feedback is an integral part to rehabilitation exercises as it allows patients to monitor their performance, promote errorless learning, and avoid compensatory movements. Virtual rehabilitation systems often have a multitude of opportunities for feedback delivery. Most systems include components for visual and auditory presentation of information which can be utilized for feedback delivery. Even tactile input through the use of pressure sensors, electrotactile stimuli, or puffs of air are potential feedback mechanisms.

Feedback can target individual performance parameters such as movement speed, trajectory, precision, and smoothness as well as more holistic parameters such as task completion or completion time. Feedback delivery can occur in real-time or as a summary after the movement or even the training session have been completed. With the proper use of feedback, the patient's attention can either be focused on individual task parameters or the movement as a whole, depending on the goal of the training session. Real-time feedback requires additional attentional resources and has to be used carefully in order to not distract from the actual task. The choice of feedback modality and presentation can facilitate the processing of feedback without too much task interference. For example, visual feedback can lend itself to outline an optimal movement trajectory while auditory feedback can indicate information about movement speed [16]. Moreover, feedback modalities should be adapted to accommodate the strengths and weaknesses of different patient populations. Exemplarily, patients with deficits in visual attention might benefit more from auditory feedback and aphasic patients might benefit most from non-written visual and non-spoken auditory feedback. Lastly and most importantly, all aforementioned feedback mechanisms can be applied dynamically and adaptively when a system's collected data is being utilized. Choice of feedback modality, frequency, and task parameters to give feedback on should be adjustable to the unique situation of each patient. Either the therapist, patient, or the virtual rehabilitation system itself should be able to change feedback parameters throughout the course of a patient's rehabilitation. As the patient's performance increases, different feedback mechanisms, frequencies, or increasingly implicit feedback might become more relevant for an optimal recovery.

(c) Precise control over scenarios

Developers of virtual rehabilitation scenarios usually have full control over all aspects of the simulation. That is, events, distractions, animations, task stimuli, and feedback can be precisely controlled to guarantee a consistent experience for each patient. Ideally, most of these parameters are then exposed in the application's interface to give the therapist control over the content of each training session. Alternatively, the aforementioned data collection capabilities allow the simulation to tweak task parameters automatically based on the user's performance and therapeutic goals. Exemplarily, error reduction or error augmentation can be adjusted dynamically to balance motivational aspects and therapeutic success over the course of therapy sessions. However, control over virtual scenarios extends much beyond the configuration of task parameters. Displaying environments and avatar movement are two key components that can have a large impact on the training scenario. Environments can range from game-like or abstract environments to more realistic simulations to suit the patient's preferences and enhance motivation. In fact, simulating environments that are otherwise inaccessible or too dangerous for patients is one of the key advantages of virtual rehabilitation tools. For example, patients can safely practice reaching for targets in a virtual supermarket which would otherwise be an inaccessible location for patients undergoing inpatient rehabilitation. The representation of the patient's movement on screen can heavily influence task performance. Moreover, it allows patients to assess their own movement and actively learn how their body movement is connected to the visual feedback they receive on the screen. The patient and his/her movements can be represented realistically or in a more metaphorical way in order to increase or take away focus from affected limbs and relevant movements. Characters, if displayed at all, can be realistic avatars, neutral mannequins, cartoon characters, or even real-time camera images of the patient (e.g., Microsoft Kinect or Playstation 2 Eyetoy[16]).

In sum, each and every aspect of a virtual scenario must be carefully considered by the developers and therapists and in best case should be highly flexible to adapt to each patient's unique circumstances.

(d) Enhanced motivation

Adherence to therapy programs is one of the most critical aspects of neurorehabilitation as high-frequency repetition of movements has been shown to be key for recovery [3, 18, 19]. Unfortunately, current therapy practices are not able to encourage patients to perform the number of repetitions required for neuroplastic changes to occur [12]. Furthermore, within the home setting, patients often lose their motivation over time as tasks become repetitive and feedback about progress is lacking or non-obvious. Virtual rehabilitation scenarios have become a popular choice for therapy, largely for their ability to motivate patients to continue their exercise regimes over extended periods of time. Game-based mechanics and features such as high scores, achievements, virtual reward items, diverse landscapes, and interesting characters are excellent ways to engage patients during their rehabilitation and clearly communicate progress over time. The implementation of game mechanics also takes away the focus from affected limbs and shifts attention to achievable goals within the game environment, thus potentially reducing

[16] http://de.playstation.com/ps2/accessories/detail/item51693/EyeToy-USB-Kamera/

anxiety. Repeating similar tasks in different game-like contexts even promotes generalization of learned behaviors which has been shown to be important for transfer to activities of daily life.

However, not each virtual rehabilitation tool needs to look and feel like a computer game. Enjoyment of game-like content or even graphics style often depend on personal preference and graphical fidelity. In some cases, a realistic simulation of a relevant real-life environment can be the most motivating scenario as long as it aligns with the patient's goals. Yet, even simple task rewards or a scoring system can go a long way to motivate the patient over extended periods of time and provide an easy-to-understand feedback system.

Increased patient motivation continues to be one of the most powerful aspects of virtual rehabilitation systems. Virtual scenarios and tasks need to be designed with a variety of content to engage patients beyond the novelty effect of the first few training sessions. After all, repetitive task practice is still thought to be the most effective means to regain motor function after neurological injuries, despite the frequent lack of patient motivation.

(e) Flexible use cases

Due to their flexible nature, virtual rehabilitation tools can be useful in a wide range of therapeutic scenarios. Virtual rehabilitation systems can be used as standalone setups for direct therapeutic interventions with any combination of the aforementioned hardware components. Such systems can be used statically in clinics and homes or as mobile setups utilizing tablets, laptops, smartphones, and head-mounted displays. Virtual rehabilitation systems can also be used as a visualization or extension for robotic rehabilitation systems or brain computer interface systems. Virtual scenarios can even be coupled to traditional exercise tools such as treadmills and cycling trainers. In each case, virtual scenarios can enhance the original therapy by adding feedback, tasks and other motivating aspects.

Lastly, the flexibility of use cases will only increase as new gaming hardware such as fully-tracked omnidirectional treadmills are becoming more mature and affordable (e.g., Virtuix Omni and Cyberith Virtualizer) and markerless tracking will support more unencumbered, natural full-body, or fine-motor movements (e.g., Microsoft Kinect 2, Nimble Sense).

Virtual rehabilitation is a very young discipline and many challenges and threats to its widespread use still have to be addressed. However, each of the advantages outlined in this section present a strong case for the adoption of virtual rehabilitation tools in clinical practice and should be encouraging for researchers and clinicians to strongly support the clinical implementation and evaluation of the outlined technologies. Many of the past threats and disadvantages of virtual reality technology that were described in 2005 [27] have already been overcome by recent technological advances. Some of the remaining challenges and threats to virtual rehabilitation tools and technologies are still existent and will be summarized and discussed in the next section of this chapter.

4 Challenges and Threats to Virtual Rehabilitation

While virtual rehabilitation has been demonstrated to have great potential to improve upon existing rehabilitation interventions and protocols, many of the proposed advantages of virtual reality systems within the clinical setting require more supporting evidence and exploration. The number of articles reporting development, usability, and feasibility of virtual rehabilitation tools has increased exponentially over the past five years. However, the research is published in a wide variety of journals and conference proceedings with a range of different keywords making it difficult to find. Many researchers and developers have published papers outlining the development process and intervention description (e.g., [4–6, 13, 26, 31]). These papers describe the underlying theories and processes used in the development of virtual reality systems for use in the clinical setting. Some of these papers are purely descriptive, however, other papers provide feedback and findings from initial assessment of patients or clinicians.

Usability and feasibility studies provide initial support for the concept for virtual rehabilitation tools and interventions. Usability and feasibility studies explore user feedback and likeability of virtual reality interventions and evaluate the potential of the intervention for clinical use prior to evaluating the system in a larger randomized comparison trial (for example [11, 21, 22, 29]).

A number of reviews of randomized controlled trials have been published recently exploring the efficacy of upper and lower limb virtual reality training for people following stroke [10, 14, 15, 20]. Overall, limited evidence exists for the use of virtual rehabilitation interventions for people with stroke. Virtual rehabilitation has been shown to be at least as good as existing therapies. While the review papers provide some support for the use of virtual rehabilitation for people with stroke, the existing research studies are variable in terms of patient population, outcome measures, intervention type, intervention dose, and intervention duration and frequency. Importantly, interventions used in existing trials range from high-end robotic devices to tailored low-cost systems and off-the-shelf video game consoles. There is little agreement and standardization across the research studies, making it difficult to compare the research and provide strong conclusions.

The following section provides an overview of the challenges and threats that the field of virtual rehabilitation is facing.

(a) Lack of standardization

Virtual rehabilitation is a very heterogeneous field with different types of technologies, design approaches, and many research groups and companies that work on the development and validation of novel technologies. With such a large and varied number of entities involved, standardization becomes a key factor in each step along the path from conceptualizing to implementing a virtual rehabilitation system. Many technologies applied in this field are new and innovative, thus lacking clear design standards. This is especially detrimental for interaction design where sensors and tracking devices enable users to interact with virtual objects in 3D space. Combining these sensors with unique display solutions

leaves developers with trial and error to arrive at design decisions. Only recently have companies behind new virtual reality hardware started to distribute design guidelines for their products that form a common basis for developing interactive systems (For example: LeapMotion,[17] Microsoft,[18] OculusVR[19]).
However, most of these guidelines are centered on specific technologies and often address the consumer market without any view for research or clinical use of these new technologies. This leaves many researchers and rehabilitation-focused companies on their own to address the problems of:

- interaction with virtual 3D objects,
- judging distances in virtual space,
- creating appropriate feedback,
- collecting and interpreting complex dataset,
- developing technology-agnostic applications,
- developing user-friendly interfaces that are intuitive for patients, caregivers, and clinicians.

Clinical data are critical to establish the feasibility, usability (ISO IEC 62366: 2007[20]), and efficacy of new rehabilitation interventions and are required according to the medical device directive [7] as long as they are intended and marketed as rehabilitation tools. It is important to show that improvements in motor function are existent, large enough to be clinically relevant, stable over time, and transfer to the patients' activities of daily life. In order to compare different interventions and decide which might be the most appropriate therapy for any given patient, it is helpful to be able to compare the outcomes of different evaluation trials by using similar outcome measures and reporting effect sizes. This is especially important for conducting meta-analyses. Unfortunately, each evaluation approach of research to date, differs substantially regarding outcome measures, patient inclusion and exclusion criteria, intervention time, and statistical analyses [10, 14, 20]. A standardization of study designs and comparability between studies, including replication studies, would greatly benefit the field of virtual rehabilitation.
Once these evaluation, development, and design standards have been agreed upon, sufficiently-powered, well-controlled clinical trials and usability evaluations must be conducted. The outcomes of the usability trials can inform the system design and implementation of future virtual rehabilitation tools. The results of clinical trials allow researchers and companies to draw conclusions about the clinical efficacy of different system components and parameters. Further, conclusions can be drawn about which system and technology is best suited for which patient population, demographic- or lesion location. A last step towards

[17] http://www.blog.leapmotion.com/inside-leap-motion-5-hands-on-tips-for-developing-in-virtual-reality/
[18] http://www.msdn.microsoft.com/en-us/library/jj663791.aspx
[19] http://www.static.oculusvr.com/sdk-downloads/documents/OculusBestPractices.pdf
[20] http://www.iso.org/iso/catalogue_detail.htm?csnumber=38594

widespread use of virtual rehabilitation tools is to use data gathered from the aforementioned trials and use them as a basis for cost–benefit analyses which pave the way for cost reimbursement and clinical adoption.

(b) Heterogeneity of evaluation trials
Three meta reviews have been published since the previous version of this chapter was written in 2012 and published in 2013. Pietrzak et al. [24] reviewed 18 studies that evaluated virtual reality and video game-based rehabilitation in patients with traumatic brain injury. Fluet and Deutsch (2013) included eight upper limb rehabilitation and two lower limb rehabilitation studies in their stroke-focused virtual reality meta review. Lastly, Lohse et al. [20] reviewed a total of 26 virtual rehabilitation studies that targeted patients with stroke. The conclusions of all three reviews are in agreement that there is much potential in the virtual rehabilitation approach, there are many open questions that remain to be answered, and, most importantly, that the reviewed studies differ substantially in fundamental aspects of patient characteristics, study design, intervention design, outcome measures and tested virtual rehabilitation systems and how each of these aspects is being reported by the studies' authors. It is this heterogeneity of conducted studies and their documentation and dissemination of results that make it almost impossible to draw much needed conclusions that could move the field of virtual rehabilitation forward. Looking at the different study characteristics the following discrepancies between studies were found:

(1) Patient population and characteristics
A detailed description that goes beyond demographics of the recruited sample is a basic requirement for researchers to draw sound conclusions across different studies and interventions. Unfortunately, all reported studies in each of the meta reviews differ substantially in describing their recruited patients and their interaction with study personnel, therapists, and caregivers. Patients with different deficit severity were tested with a wide range of reported standardized measures. While sensory and cognitive abilities were often reported as required inclusion criteria, no actual measurement of these domains were quantified in most studies. This is a critical point, as there is only very limited knowledge about how sensory and cognitive deficits impact the utility of virtual rehabilitation systems for treatment of stroke and traumatic brain injury patients. A more detailed description of motor, cognitive, and sensory abilities of the recruited samples was demanded by Fluet and Deutsch (2013), who also suggested sample stratification whenever appropriate sample size and range of deficit severity were given. Overall, sample sizes were rather small in most reported studies (e.g., 5–40 in Lohse et al.'s review) and mostly not justified by power analyses. Inclusion of acute, subacute, and chronic patients differed between studies, but was consistent within each study that was being reviewed.

(2) Study design
There were large differences in the design and characteristics of the reviewed studies. Studies often differed in their administration and comparison of

experimental treatment and control treatment. Exemplarily, Lohse et al. describe that only 61.5 % of their reviewed studies reported blinded experimenters, 61.5 % reported similar groups based on comparisons of baseline performance. Blinding participants and therapists to treatment allocation or study hypotheses were only reported in 19.2 and 3.8 % of all studies respectively.

(3) Intervention characteristics
Intervention intensity, frequency, and overall duration differed substantially between the reviewed studies. Lohse et al. reported virtual reality interventions ranging from 180 to 1800 min in total training duration. Pietrzak et al. mention a more consistent intervention schedule for the studies they reviewed, ranging from eight to twelve sessions, three times per week. Training sessions ranged from 30 to 90 min per session. Fluet and Deutsch report study durations between four and twelve weeks and on average 10.5 h of upper limb training and 7.5 h of gait training. Almost none of the reviewed studies in each of the three reviews control for the number of repetitions completed by the participants, which provides no basis for establishing a dose–response relationship between training time and outcome measures.
Treatment progression can either be achieved automatically through algorithms or manually through observation of the clinician or user. Both options are reported frequently, but descriptions of criteria for each progression mode are often lacking. Different variables underlying the progression algorithms further complicate the comparability of learning curves and outcomes of different virtual rehabilitation interventions. Lastly, difficulty parameters which are changed as the patient progresses through the intervention differ between each study and no clear relationship between these variables and intervention efficacy has been established yet.

(4) Virtual rehabilitation systems
Arguably the largest variability between all conducted studies comes from the tested rehabilitation systems themselves. Stark differences in input and output modalities, provided feedback, system components such as tracking systems, robotic devices, or brain computer interfaces were all reported in the three assessed reviews. System complexity and cost ranged from off-the-shelf gaming systems for a few hundred dollars (e.g., Nintendo Wii,[21] Microsoft Kinect) to custom-built, one-off rehabilitation devices to large immersive rehabilitation systems for several hundred thousand dollars (e.g., Motek Medical's CAREN system[22]). Comparing outcomes between these different systems can potentially outline the different options that are available for therapists. However, drawing conclusions about the efficacy of different system components for various subgroups of stroke and traumatic brain injury populations remains a large challenge which can only be

[21] https://www.nintendo.de/Wii/Wii-94559.html
[22] http://www.motekmedical.com/products/caren/

overcome if common frameworks for system design, task delivery and feedback mechanisms are considered.

(5) Patient Motivation

While patient motivation is expected to play a large role in the success of virtual rehabilitation systems, motivation is rarely ever mentioned or measured in any of the reviewed studies. Only few studies attempted to use entertaining or motivating tasks such as card games or video games for their control groups [20]. Most evidence to support the increased motivation of virtual rehabilitation tools seems to stem from anecdotal reports or unstructured interviews during debriefing sessions. Clearly, more evidence and stricter controls for the motivating factors of experimental and control interventions are needed to clearly establish the motivating advantage of virtual training scenarios.

(6) Outcome measures

All three reviews report outcome measures at all levels of the International Classification of Functioning, Disability and Health (ICF). Utilized measures differ substantially and include variables produced by each virtual rehabilitation systems and standardized measures of motor function, activity, and participation.

In conclusion, all reviewed studies differed dramatically in all aspects that are relevant for drawing conclusions about the overall efficacy of the virtual rehabilitation approach. In order to establish the merit of different system components and intervention methodologies for different patient characteristics, it is necessary to find common ground for the design and evaluation of these new technologies.

(c) Assumes ability to move

Tracking systems and sensors usually require the patient to have at least a minimal amount of movement or range of motion. This can be problematic with heavily impaired patients who might require assistive devices such as robotic systems, exoskeletons, or braces to interact with virtual rehabilitation systems. Symptoms such as tremor or spastic paresis can also interfere with accurate tracking as small hand movements and self-occlusion for clenched fists and spastic movements can be problematic for visual tracking systems. Moreover, many tracking devices are designed for healthy users and support use in standing or seated positions and might not work properly with patients who cannot leave their bed. Consequently, feasibility and usability trials need to shed light on the correct choice of technology for patients with varying range of movement capabilities and symptoms which might interfere with the proper use of virtual rehabilitation systems.

The majority of patients with upper limb paresis are treated predominantly during the subacute or chronic phases post-stroke or traumatic brain injury (greater than 3–6 months). Treatment during acute phases frequently becomes impractical due to medical instability or severe paresis of patients. However, some evidence supports the view that corticospinal connections and neuroplastic changes can be facilitated by upper limb motor training in acute phases post injury [28]). Consequently, virtual rehabilitation training could also be feasible and beneficial, even in early stages after neurological injuries for improving motor tasks execution and motor hand function [2, 33].

(d) Perception of technology
New technologies can be daunting to therapists and patients alike, especially if they have the label "virtual reality" or "virtual rehabilitation" attached. Therapists may perceive new technologies as threats which are taking over their responsibilities and ultimately their jobs. Conversely, patients may not have any experience with computers or video games and can be intimidated by large virtual rehabilitation systems or the prospect of wearing a head-mounted display. While new systems can be wireless and much less complex than traditional virtual reality setups, the preconception of large, uncomfortable systems that cause nausea and eyestrains while also taking diagnostic and therapeutic decisions away from the therapist still exists.

Many challenges of the past decade have been addressed with recent advances of mobile computing, low-cost HD-displays and virtual reality gaming hardware. What remains are threats that technology cannot solve on its own. Companies and researchers need to agree on design and evaluation standards to start a comprehensive effort toward validating virtual rehabilitation tools as viable alternatives to traditional therapy. Such potential success stories and increased market uptake of virtual rehabilitation tools might also change the perception of these technologies as niche products and scary visions of the future.

5 Conclusions

This chapter aimed to provide an update to the current state of the field of virtual rehabilitation regarding technological and clinical advances since the previous version of this chapter was published in 2013 [23]. Most recent progress in virtual rehabilitation seems to come from technological innovations in mobile computing, low-cost motion-tracking and sensing devices, the appearance of low-cost HD displays, and affordable virtual reality gaming hardware. Research and clinical validation of virtual rehabilitation tools seems to focus on small feasibility trials and validation of customized tools that do not allow to draw conclusions about the generalization of efficacy across technologies and tools. Moreover, transfer of gained abilities to the patients' activities of daily life is still sparse and often not addressed in recent published research.

In conclusion, there seems to be a large gap between the technological possibilities that virtual reality hardware and software provide and the transfer of this potential into actual clinical use via the design, development, and implementation of standardized virtual rehabilitation tools and protocols. It is of utmost importance that systematic evaluations of optimal task design, interaction design, feedback delivery, and technology selection for each individual patient or patient population are conducted. Such studies should then be leveraged for the dissemination of guidelines, common platforms, frameworks, and, ultimately, cost–benefit analyses that provide a strong argument for the implementation and reimbursement of virtual rehabilitation tools. First steps toward development and evaluation guidelines have already been undertaken through recent meta-analyses and publications that bring together principles of motor learning and virtual reality technology [17]. However, a more coordinated effort between researchers, companies, and policy makers is required to push the field of virtual rehabilitation toward widespread clinical adoption.

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