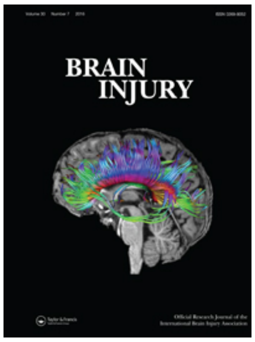

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REVIEW ARTICLE

Virtual reality gaming in the rehabilitation of the upper extremities post-stroke

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Abstract

Background: Occurrences of strokes often result in unilateral upper limb dysfunction. Dysfunctions of this nature frequently persist and can present chronic limitations to activities of daily living.
Methods: Research into applying virtual reality gaming systems to provide rehabilitation therapy have seen resurgence. Themes explored in stroke rehab for paretic limbs are action observation and imitation, versatility, intensity and repetition and preservation of gains. Fifteen articles were ultimately selected for review. The purpose of this literature review is to compare the various virtual reality gaming modalities in the current literature and ascertain their efficacy.
Results: The literature supports the use of virtual reality gaming rehab therapy as equivalent to traditional therapies or as successful augmentation to those therapies. While some degree of rigor was displayed in the literature, small sample sizes, variation in study lengths and therapy durations and unequal controls reduce generalizability and comparability.
Conclusions: Future studies should incorporate larger sample sizes and post-intervention follow-up measures.

Keywords

Gamification, commercial game system, Nintendo Wii, Microsoft Xbox Kinect, Sony PlayStation EyeToy, head-mounted display, interactive rehabilitation

History

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Introduction

A functional burden of stroke

Cerebral vascular accidents or strokes occur in roughly 795 000 people annually in the US [1]. Upper limb deficits have been shown to occur in up to 85% of sufferers of stroke. These dysfunctions are persistent in 55–75% of this population 3–6 months post-stroke and significantly affect the activities of daily living (ADL) performed by these patients who are afflicted [2].

Incorporating virtual reality into stroke rehabilitation

Physical and occupational rehabilitation therapies of sufferers of stroke with some level of hemiparesis are well established in both the inpatient and outpatient settings. The concept of incorporating virtual reality (VR) technologies into rehabilitation therapies, although not new, has seen resurgence in popularity among researchers in the last decade. Arguably the advent of VR integrated gaming systems such as the Wii and Xbox Kinect, which increased the availability and affordability of the technology, are owed some of the credit for this phenomenon.

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While there has been an increase in the published literature on VR rehabilitation therapies over the last decade, many new studies have come to light since 2009. A review of the current literature is now warranted to establish a fresh benchmark for future research.

A neurobiological foundation

Several themes are present in the current rehabilitation literature. The foremost theory cited in VR research is based upon the mirror neuron system. First identified in the premotor cortex of monkeys, the mirror neuron system allows humans and other primates to understand the observed actions of others and to subsequently imitate those actions [3,4]. Mirror neurons or activity that suggests their existence have been observed in studies that employ electroencephalographic suppression in humans [5]. This discovery has reverberated in the field of stroke rehabilitation as a means for re-teaching paretic limbs how to function.

The advantage of a modifiable rehabilitation environment

A related secondary theme in the VR rehabilitation literature is the versatility of VR technology. Patients suffering symptoms as an outcome of a stroke are able to distinguish kinematic details in observed movements. Their ability to distinguish fluency of movement, however, can be more variable than those made by healthy individuals. It has been hypothesized that this is due, in part, to a lower tolerance for distracting or superfluous data in patients post-stroke as a consequence of altered brain functioning and the greater effort required to make kinematic judgements. There is evidence to suggest that tailoring the rehabilitation environment, via a modifiable VR display, to present only the most important kinematic information, such as basic representations of involved limb motion and trajectory, will result in a more accurate understanding of the movement by patients with stroke [6].

Repetition and intensity of movement are, also, thought to aid in the rehabilitation of paretic limbs. Neural plasticity suggests that many repetitions are required to improve function in a paretic extremity [7]. There is, also, evidence that more intense rehabilitation effort in the acute phase yields small, but significant improvements in patients with stroke [8]. Some researchers investigating VR rehab therapy for patients post-stroke have placed an emphasis on optimizing repetition counts and the intensity of rehab therapy. While this line of research is not unique to VR therapy, it has been suggested that it is particularly applicable to the readily modifiable VR environment [9].

The persistence of functional gains associated with VR rehabilitation

A final theme that will be addressed in this review is the question of how well any functional gains made through a rehabilitation intervention are retained over an extended length of time. The evidence suggests that rehabilitation therapy is more effective if conducted over an extended length of time. In addition, improvements can be lost if a paretic limb is not utilized to its full functional ability once formal rehabilitation has ended [7]. Studies that include post-intervention follow-up measurements give a more realistic picture of the potential long-term benefits of VR therapy.

State of the literature prior to 2014

Evaluation of the literature prior to 2014 uncovers multiple concerns that call into question the robustness of the research. As demonstrated in Table I, the studies, to date, have shown promising results for upper arm and ADL function. However, due to limitations inherent with the study designs, the results have not been conclusively proven. Small sample sizes are the norm in this field of research. A lack of standardization in evaluation criteria among the various VR interventions makes direct comparison or aggregation of data difficult. Further compounding the issue are the interventions themselves, which employ varying degrees of immersion into the VR environment and hybridization with complementary technologies such as robotics, making pure assessments of the VR therapy problematic [10,11].

Also, in question are the long-term benefits of VR rehabilitation. Missing from the literature are well designed studies that incorporate periodic follow-up testing of the original study measures post-completion of the VR rehabilitation. Rehabilitation of a paretic limb can require prolonged therapy. In order to establish the benefits of VR rehabilitation with any accuracy, the persistence of its effects must be established in relation to the duration of the intervention [11].

Methods

A review of the current literature was conducted by employing a Boolean search of CINAHL, PubMed and Google Scholar databases. Search terms applied to the database included: *stroke, CVA, rehabilitation, rehab, virtual reality, gaming* and *gaming console*. Several pertinent articles were identified through PubMed's *related citations* feature. Additional relevant studies were located through a review of the reference lists from previously identified articles. The criteria for inclusion was English language, peer reviewed journals published no earlier than 2009. Thirty-five published research articles pertaining to the use of VR gaming in the rehabilitation of patients post-stroke were initially reviewed. Articles were included in the final review based on their relevance to upper extremity rehabilitation. Fifteen articles were ultimately accepted into the literature review.

Review of the literature

Commercial game systems

The sixth and seventh generation gaming systems are currently being utilized for VR rehabilitation therapy. The VR offered by these systems are considered non-immersive. These include the Nintendo Wii, Sony PlayStation 2 EyeToy and the Xbox 360 Kinect. Non-immersive VR systems employ the use of only one sensory modality, are cheaper, easier to use and prone to fewer adverse effects [12]. These systems are ubiquitous in modern society and, although no longer the current generation of gaming system, still readily available and supported by their parent companies.

Nintendo Wii

The Wii gaming system was released by Nintendo in 2006. A new basic Wii console retails between $99.00 and $129.00 on Nintendo Wii's official site (https://www.nintendo.com/wii, May 2014). Used and refurbished consoles can be acquired at a further discount. The system utilizes a wireless game controller, which houses a gyroscope and an accelerometer. The controller is tracked by a light bar that can be calibrated for use either immediately above or below a Wii connected television screen.

The Wii was studied as an adjunct to conventional rehabilitation therapy by Joo et al. [13]. All participating patients were within 3 months of a stroke, which resulted in upper limb weakness. A convenience sample of 16 patients completed the study. The patients participated in six sessions, lasting 30 minutes, over a 2-week period. During the intervention period, the patients were concurrently receiving at least 1 hour of occupational therapy (OT) and at least 1 hour of Physical Therapy (PT) Monday–Friday. The games selected for the study were Wii Sports boxing, bowling, tennis, golf and baseball. Upper limb function, as measured by the Fugl-Meyer Assessment (FMA) and motor power of the shoulder, elbow and fingers, as measured by the Motricity

Table I. Summary of results from the literature search.

VR rehabilitation system	Study	Outcome measures	Results
Nintendo Wii	[13] [12] [14]	Fugl-Meyer Assessment (FMA) and Motricity Index (MI) Wolf Motor Function Test (WMF) and FMA WMF and Box and Block test (BBT)	Significant improvement in upper extremity (UE) function and motor power of the shoulder, elbow and fingers. The WMF showed a decrease in the time tests and an increase in the weight lifting task. Motor function in the VR group showed greater improvement than in the conventional therapy (CT) group. Both groups showed improvement in the BBT.
Microsoft Xbox Kinect	[15] [16]	FMA, BBT and active range of motion (AROM) by goniometer Manual Muscle Test and Functional Independence Measure (FIM)	The intervention group demonstrated greater improvements than the control group in all outcomes except wrist range of motion. Muscle strength in the UE, excluding the wrist and ADL performance improved from baseline in the VR group.
Sony PlayStation EyeToy	[17]	Activity counts and the intensity of movement via accelerometers	The Sony EyeToy produced higher activity counts among the healthy adult group and greater movement intensity in both the stroke and healthy group than the Nintendo Wii.
Caren 3D Virtual Environment	[18]	Clinical and Kinematic assessments	In the intervention group, mildly impaired participants displayed greater elbow extension, shoulder horizontal adduction and flexion at extension. Moderate-to-severe participants showed increases in arm use and reaching ability.
Novel VR Rehab Incorporating Head-Mounted Display	[19]	MI and the Action Research Arm Test	No significant improvement in either the control or intervention groups. Transient dizziness and headache experienced by two participants in the VR group.
Virtual Reality Rehabilitation System (VRRS)	[20]	FMA and FIM	The VRRS plus CT resulted in higher scores in both measures than CT alone.
Virtual Reality Rehabilitation System VRRS.net	[21]	FMA, ABILHAND scale and the Ashworth scale	Functionality and spasticity of the UE improved in the CT and VR groups. Greater gains were seen in the FMA scores of the VR group.
Interactive Rehabilitation and Exercise System (IREX)	[22]	FMA, Motor Function Test and the Korean Version of Modified Barthel Index	The VR group improved in both motor function tests, while the CT group only showed improvement in the FMA. Gains in ADLs were measured in both groups.
Rehabilitation Gaming System (RGS)	[23] [24] [25]	FMA and Chedoke Arm and Hand Activity Inventory (CAHAI) Barthel Index, MI, Ashworth, FMA, CAHAI, BBT MRI brain scans	RGS group showed more improvement in UE functionality than the CT group. No significant differences were noted in hand movement. RGS-H group measured better at gross manual dexterity. No other significant differences between the groups at post-test. At 12-week follow-up, the RSG-E group exhibited poor retention of gains in UE functionality. The RSG-H group retained all UE gains. Operation of the RGS corresponded with activation of areas of the brain associated with executing, observing or imagining goal-directed action.
Telemedicine System Empowering Stroke Patients to Fight Back (StrokeBack)	[27] [28] [29] [30]	WMF, Barthel index Clinical and Kinematic assessments Sensor measurements	The StrokeBack study was accompanied by a few standard rehabilitation tests and measures to assess the success of rehabilitation means. The patients were very well motivated. The evaluation of results is in progress.

Index (MI), showed significant improvement at post-test. Two patients reported lethargy and fatigue during the first session and left the study, while three other participants reported transient soreness of the upper limb during the course of the trial; 87.5% of the patients reported that they would like to continue to use the Wii VR therapy as part of their rehabilitation programme.

Mouawad et al. [12] completed a pilot study, which investigated the efficacy of the Wii gaming system in the rehabilitation of patients post-stroke who are hemi-paretic. The study recruited a convenience sample of seven participants. The participants played Wii sports games such as tennis, golf, boxing, bowling and baseball for 14 days. During the 10 consecutive weekdays within the period, 1 hour of supervised training was provided in a laboratory. The participants were given a second Wii console for home use. Home use progressed from 30 to 180 minutes per day. A second, healthy, group was utilized to control for such confounding effects such as skill acquisition and new learning. Increases in functional ability were tested using the Wolf Motor Function Test (WMF) and the FMA. The WMF, which involves two strength tests and 15 timed tests, showed a mean time decrease from 3.2 to 2.8 seconds per task ($p < 0.001$) in the time tests and an increase in the weight lifting task from 8.6 ± 2.6 lb to 11.4 ± 2.9 lb ($p = 0.018$). ADLs were assessed via the completion of three Quality of Movement Scales of the Motor Activity Log (QMSMAL). The QMSMAL is a self-rated assessment, which logs the degree of use for the paretic limb in everyday tasks. Scores improved significantly over the course of the study. Three of the original intervention patients were re-evaluated 2 months after the completion of the primary study. WMF scores were not only retained for these three patients, but increased moderately. Post-study therapy was not regulated during this time period and raises the question of whether these particular patients continued to independently use the Wii in a therapeutic fashion, another undisclosed therapy or a combination of therapies post-study.

A randomized controlled pilot study by Saposnik et al. [14] added a modicum of needed rigour to the literature supporting the use of the Nintendo Wii as a stroke rehabilitation tool. However, the study was primarily designed to test the feasibility of Wii VR therapy and efficacy of treatment was tested as a secondary outcome. Participants for the study were within 6 months post-stroke. The VR group (n = 9) underwent eight sessions, over 14 days, lasting for 60 minutes each. Wii games selected for the trial included bowling, tennis, and Cooking Mama. Patients in the rehabilitation control group (n = 8) were tasked with participating in card playing, stamping a seal during a bingo game or Jenga. All patients in the study received 1 hour of physiotherapy and 1 hour of occupational therapy throughout the course of the trial. Primary outcomes tested in the study were for length of intervention time and safety. No serious adverse effects were reported in either group. Both the standard rehabilitation group and the VR group completed statistically similar durations of therapy over the 2 weeks of the trial. As a secondary outcome, efficacy of treatment was measured by the WMF. Motor function in the VR group post-intervention showed significantly greater improvement than the rehab group. Significant improvement was seen in both groups on the Box and Block test (BBT), which tests gross manual dexterity, although no significant difference was seen between groups.

Microsoft Xbox Kinect

Microsoft's Xbox Kinect (360 version) is a commercially available VR gaming system, retailing for ~ $250.00, that does not require the aid of a controller to manipulate a virtual environment. The Kinect system instead utilizes an infrared camera to capture in real-time a user's movements, which it then projects into the VR gaming environment. As it does not require the manipulation of a controller, the Kinect is not reliant on a baseline level of fine motor skill in the paretic limb.

Sin and Lee [15] conducted a randomized controlled trial to test the Xbox Kinect's ability to aid in upper limb rehabilitation post-stroke. The 40 participants recruited for the trial were evenly split between the intervention and the control groups. Average time elapsed post-stroke in the intervention group was 7.22 months and 8.47 months in the control.

The control group underwent 30 minutes of conventional OT 3-times a week for 6 weeks. The intervention group received the same OT as the control group, but with an additional 30 minutes of VR therapy prior to the OT for the duration of the study. VR therapy consisted of various games from the Kinect sports pack and Kinect adventure pack. The outcome measures, evaluated pre- and post-study by blinded OTs, were the FMA to assess motor function, the BBT to assess manual dexterity and active range of motion (AROM) captured by a goniometer. While both groups displayed significant improvements in all outcome measures, the intervention group demonstrated significantly greater improvements than the control group in all outcomes except wrist range of motion. However, due to the greater overall therapy time experienced by the intervention group it is unclear if the VR therapy is responsible for the enhanced benefits exhibited by this group.

Lee [16] oversaw a small (n = 14) randomized controlled trial to evaluate the effect of VR therapy utilizing the Xbox Kinect on muscle strength, muscle tone and ADLs in patients who had suffered a stroke greater than 6 months prior to the study. Similar to the previous study, the control group received 30 minutes of conventional OT 3-times a week for 6 weeks, while the intervention group received the same amount of OT as the control with an additional 30 minutes per session of VR therapy with the Kinect. The selection of game titles available to the participants was identical to Sin and Lee's [15] study. Muscle strength, measured by the Manual Muscle Test, showed significant improvement in the VR group from baseline throughout the upper extremity, excluding the wrist. ADL performance, also, improved significantly from baseline in the VR group, as measured by the Functional Independence Measure (FIM). However, no significant differences were measured between the control and VR groups at post-test.

Sony PlayStation EyeToy

The Sony EyeToy is a small camera, which retails for $10.00–$20.00. It is compatible with the PlayStation 2, which retails for $110.00–$120.00 new. The EyeToy utilizes video capture software to project the image of the user onto a virtual environment. Neil et al. [17] attempted to compare the Sony EyeToy to the Nintendo Wii in terms of usability and user experience and frequency and intensity of activity. The authors designed a small cross-sectional study of patients, who had a stroke at least 12 months prior to the study. Ten adults post-stroke and 10 healthy adults were recruited into the study. A questionnaire was utilized to gauge the participants' perceived satisfaction, enjoyment and usability of the systems. No significant differences were found for these measures. However, through the use of accelerometers strapped to the participant's wrists, the authors were able to measure activity counts and the intensity of movement. The Sony EyeToy produced significantly higher activity counts among the healthy adult group and significantly greater movement intensity in both the stroke and healthy group as gauged by the accelerometers. The study, although limited by size and lack of randomization, does suggest that video capture technology may potentially elicit greater and more intense activity.

Novel VR rehabilitation gaming systems

Caren 3D virtual environment

Subramanian et al.'s [18] small (n = 32) double-blind randomized controlled study utilized a virtual environment (VE) game to enhance outcomes during upper extremity intensity-matched training. Such training employs the use of high numbers of repetitious movements to elicit motor improvements. The employed intervention, a 3D virtual environment (VE) by CAREN, simulates a supermarket scene, in which study participants interact with products on a virtual shelf. Height of the shelves with their accompanying products and overall look of the VE was mimicked in a physical environment to create a control setting. The intervention and the control group underwent 12 sessions each over 4 weeks, with each session averaging 45 minutes. The environments were designed to employ equivalent practice intensity, frequency and feedback. Additional attributes contained within the VE intervention were a visually appealing interface, game score for successful reaches, and minor supplemental visual feedback for successful target selection. Clinical and kinematic assessments were completed prior to the study, immediately after completion of the intervention and 3 months post-intervention. While both groups showed overall improvement, the VE group showed greater improvements in some areas. The mildly impaired participants in the intervention group displayed greater elbow extension, shoulder horizontal adduction and flexion at extension. The moderate-to-severe participants of the intervention group showed increases in arm use and reaching ability.

Novel VR rehabilitation incorporating head-mounted display

Crosbie et al.'s [19] small ($n = 18$), but randomized controlled trial recorded modest but non-significant improvements for both a VR intervention and a conventional therapy (CT) intervention. The VR system tested in this study is unique in recent literature for the use of a head-mounted display unit, which results in a more immersive VR experience. Arm motion was tracked by three sensors mounted on the shoulder, elbow and hand, respectively. Participants in the intervention played unspecified reaching and grasping games facilitated by a therapist, who could modify the difficulty of the program from an integrated desktop computer. The therapy in this study consisted of three sessions a week over a 3-week period, with each session lasting for 30–40 minutes. Outcomes were measured with the upper limb MI and the Action Research Arm Test, neither of which was able to record a significant improvement in either the control or intervention groups. The authors observed that the patients willing to participate in the trial tended to measure low in disability at baseline and postulated that the measures chosen for the trial were not sensitive enough to show significant small-to-moderate changes. It is worth noting that two of the nine participants in the VR intervention group experienced transient dizziness and headache during therapy. Until there are more studies incorporating head mounted displays, which include measures for adverse effects, a modicum of caution should be displayed by researchers utilizing this technology.

Virtual reality rehabilitation system

Turolla et al. [20] published a controlled study which investigated the efficacy of the Virtual Reality Rehabilitation System (VRRS). The VRRS utilizes a, '… computer workstation connected to a 3D motion-tracking system and a high resolution LCD projector …' ([20], p. 3). The VR therapy required the patient to manipulate a physical object equipped with a receiver in a virtual environment. A therapist was always present to manage the VR therapy. This study employed the largest sample population ($n = 376$) to date. Participants were allocated to either an upper limb conventional (ULC) rehabilitation group ($n = 113$) or the VR group ($n = 263$). Both groups held sessions over a period of 5 days a week for 4 weeks. The ULC group session lasted for 2 hours, while the VR group regimen consisted of 1 hour of VRRS rehab plus 1 hour of ULC rehabilitation.

The outcome measures chosen by the authors were the FMA upper extremity and the FIM. The VRRS plus ULC therapy resulted in significantly higher scores in both measures. Although the study population was not randomized and the sizes of the sample groups were markedly unequal, the large overall sample size of the study adds credence to the results.

VRRS.net

Piron et al. [21] investigated the telerehabilitation application of the Virtual Reality Rehabilitation System, or VRRS.net. The system utilized the same 3D motion tracking system as the one described in Turolla et al.'s [20] study, as well as the practice of equipping a physical object with a receiver, which allows the object to be projected and tracked in the VR environment. The telemedicine intervention required one dedicated PC for the patient's home and a second PC at the rehabilitation centre. The rehab PC had the added functionality, via a videoconferencing tool, of allowing the user to manipulate the patient's camera to observe their movements. Piron et al. [21] employed a randomized single-blind controlled approach. The author recruited 36 patients from mild to moderately unilaterally paretic, 7–32 months post-stroke to participate. The VR group underwent 1 hour sessions of VR therapy in their homes 5 days a week for 1 month. The CT group was treated with conventional physiotherapy in their local health district for an equivalent amount of time as the intervention group. Significant gains were measured for both groups in functionality of the upper extremity through the FMA and the ABILHAND scale and in spasticity via the Ashworth scale. However, significantly greater gains were seen in the FMA scores of the VR group compared to the control group at post-test. Improvements in both groups were sustained at a 1-month follow-up assessment.

Interactive rehabilitation and exercise system

Kwon et al. [22] conducted a double-blind randomized controlled clinical trial, which tested the potential efficacy of GestureTek's Interactive Rehabilitation and Exercise System, or IREX, as an adjunct to conventional rehabilitation therapy. Patients ($n = 26$) admitted to the study had suffered a stroke within the last 3 months, which resulted in one upper paretic limb. Patients were evenly allocated to either the CT group or the intervention group, which completed CT with an additional 30 minutes of VR training for 5 days per week over 4 weeks. The IREX VR system consists of data capture gloves and a video camera system, which captures the user's image and projects it onto a television screen. Users are then able to manipulate virtual objects within the context of various VR games that require reaching and lifting motor skills. The VR group showed significant improvement in both of the measures selected to test motor function, the FMA and the Motor Function Test, while the CT group only showed significant improvement in the FMA. Significant gains in ADLs by both groups were measured with the Korean Version of the Modified Barthel Index. The study results must be viewed with caution due to the small sample size and the possibility that the results are the product of the additional therapy time expended on the VR group and not due to the nature of the intervention.

Rehabilitation gaming system

Cameirao et al. [9] proposed the customization of a neurorehabilitation VR system called the Rehabilitation Gaming System (RGS) through the creation of a Personal Training Module (PTM). RGS hardware requirements are a PC, webcam and two 5DT data gloves. The PTM was developed for use with a specific game called Spheroids, which tasks the user with attempting to intercept virtual balls that are propelled towards the user's screen. The system utilizes a custom motion capture system called AnTS to map the patient's arm movements into the virtual environment by tracking coloured markers positioned along the users arms. The user then manipulates data gloves to 'grasp' a sphere. The PTM proposed by the authors is predicated on the notion of optimizing motivation and learning. To this end, the guiding principle behind the development of the PTM is to present an experience, which is interesting and challenging, but is not so demanding as to engender frustration. The PTM makes autonomous calculations based upon the user's performance in the game. Calculations for performance are based on measurements of speed, interval (between spheres), range (of spheres across the virtual environment) and size (of the sphere). Beginning with the initial calibration, the difficulty level is refined and adjusted with every additional interaction with the user. Separate calibrations are made for individual arms resulting in appropriate difficulty settings for the paretic and non-paretic arms.

The PTM augmented RGS system was subsequently employed in a small randomized controlled pilot study, which focused on patients in the acute phase of a stroke [23]. The inclusion criteria for the study required that intervention participants ($n = 8$) be within 3 weeks post-stroke and display a severe-to-moderate deficit. In addition to traditional physical and occupational therapy, the patients participated in three 20-minute RGS sessions a week over a 12-week period and included a 24 week follow-up. At week 12, the RGS group achieved significantly better outcome measures in the arm sub-part of the FMA and the Chedoke Arm and Hand Activity Inventory (CAHAI) than the control group. However, no significant differences were noted between the intervention and the control groups in hand movement. The authors of the study theorized that the incorporation of additional technology with the RGS therapy, which increases sensorimotor feedback, may be required to increase gains in hand movement. This theory would inform later research on the RGS system. No significant improvements or declines in function were seen in either group at follow-up.

The Cameirao et al. [24] study investigated ways in which to exploit complementary technology to maximize recovery of the affected upper extremities of patients with stroke. Forty-four patients with stroke were randomly assigned to one of three RGS modes. The first mode was the traditional RGS set-up, but without the use of data gloves as the other two modes would not allow manual grasping. The second (RGS-H) was the RGS coupled with a haptic interface consisting of two mechanical arms, which provide additional sensory feedback when interacting with virtual objects. The third mode (RGS-E) coupled the RGS with a bimanual passive exoskeleton, which would provide support for the arms during the exercise. Significant gains were experienced throughout the three intervention groups. The RGS-H group measured significantly better than the other intervention groups at the BBT, suggesting efficacy in hand and wrist functionality. No other significant differences were observed between the groups in overall performance at post-test. However, differing patterns of retention were noted at follow-up. At the 12-week post-intervention follow-up, the RSG-E group exhibited a low degree of retention for the previously measured gains in upper extremity functionality. The authors theorize that this is the result of the supporting exoskeleton's restraint on range of motion and the accompanying stultification of compensatory movement strategies. This is in contrast to the RSG-H group which was shown to retain all of the upper extremity gains from the intervention. The authors attribute this result to the increased sensorimotor feedback contributed by the haptic arms and the subsequent increased stimulation of what have been termed mirror neurons.

Prochnow et al. [25] investigated the neurobiological foundation for the RGS system by examining MRI images. The theoretical foundation for the RGS is based on '... visuomotor processing that includes action observation, object oriented action planning and feedback of the successful action' ([25], p. 1441). This theory is, in turn, based on neurobiological research into portions of the brain, which are associated with mirror neurons. The inferior parietal lobe (IPL) and the inferior frontal gyrus (IFG) have been shown through MRI studies to be more active during periods of executing, observing or imagining goal-directed action [26]. In order to test the neurological theory upon which the RGS is based, Prochnow et al. [25] recruited 18 healthy volunteers to operate the RGS, while undergoing MRI scans of their brains. The MRI images demonstrated activation, '... of the left SMA, left IFG, the left posterior insula, the left postcentral gyrus, the left IPL, and the right cerebellum' ([25], p. 1445). It is thought that the activation of the mirror neurons in these sections of the brain facilitates learning and re-learning processes that can aid in stroke rehabilitation [26].

StrokeBack system

The goal of the Telemedicine System Empowering Stroke Patients to Fight Back 'StrokeBack' project [27] is to improve the speed and quality of stroke recovery by the development of a telemedicine system which supports ambulant rehabilitation at home settings for patients with stroke with minimal human intervention [28]. The 'StrokeBack' system combines a range of state-of-the-art technologies from augmented/virtual gaming environments that join with immersive user interfaces for delivering mixed reality training environments. The games in the 'StrokeBack' system were all developed for therapy purposes. In the therapists' hands, all the games become a device which amends the traditional therapy and gives the opportunity to practice movements dedicated for WMF tasks. With the help of level editor surface the therapist has the opportunity to create a unique, personalized action programme for each patient, which helps the therapists' work to extend. The computer-aided e-healthcare used programs amend and, after the learning process, may even relay the presence of the healthcare professionals. The telemedicine system, besides kinesitherapy, accomplishes the aim to reach a greater self-dependence of the patients [29,30].

Discussion

Robustness of the literature

Several of the studies reviewed in this work benefit from robust study designs. Eleven of the studies reviewed here employ controlling elements and eight of the studies introduced randomization into their control designs. However, the literature still displays many of the problems that have plagued earlier studies.

The literature continues to display little standardization across studies. Fourteen different outcome measures were found to be used in the reviewed literature, ranging from upper extremity functioning, muscle tone, muscle strength, ROM, repetitions, intensity, spasticity, dexterity and ADLs. The FMA was used as an outcome measure in seven of the reviewed studies. The FMA, which measures the functional ability of the upper extremity, does allow some limited comparison between the studies.

The Wii, Xbox Kinect, VRRS, IREX and the RGS were all reviewed with studies that incorporated the FMA. All of these studies reported improved scores on the FMA post-intervention. The Xbox Kinect, VRRS, and RGS reported outcomes for the FMA that significantly surpassed their controls. However, as each of the studies incorporated different controls and intervention lengths, no further value assessment can be made.

Study size continues to be problematic for the generalizability of VR therapy efficacy. The study of Turolla et al. [20] did mitigate this trend to some extent by employing a much larger controlled study of the VRRS ($n = 376$). The non-immersive and relatively basic design of the VRRS makes it a good candidate for generalizing VR therapy efficacy.

Differences in intervention durations and study durations, as well as the unknown degree of conventional therapy received by the patients concurrently with the VR interventions continue to confound direct comparison between studies.

One novel addition to the literature contained in this review is Prochnow et al.'s [25] study of MRI brain scans of healthy individuals using the RGS system. The inclusion of imaging evidence to establish a neurobiological foundation based upon the theorized mirror neuron system adds significant credence to the RGS's theoretical basis.

Comparison between commercial and rehabilitation VR gaming systems

In many cases, direct comparison between the systems is difficult due to the problems listed in the previous section. Costs for the rehabilitation-specific gaming systems are not readily available. On the other hand, pricing for the commercial gaming systems is well known and can be considerably less expensive, especially if procured used or refurbished. The commercial systems are easy to procure, use, install and transport and relatively inexpensive to replace. The rehabilitation-specific systems contain the added expense of requiring a licensed physical or occupational therapist to control the VR therapy environment.

All of the systems provide visual feedback and afford the user the opportunity to observe virtual limb movement. The design of the gameplay is different between the commercial and the dedicated rehabilitation systems. Gameplay for the commercial systems is designed to be polished and entertaining, which can increase motivation and enjoyment. This creates added replay value for the patient and can motivate longer durations of use and more frequent use of the system. The rehabilitation-specific systems are designed to be entertaining, but are more minimalist in design and instead focus on presenting easily recognizable avatar limb movements. A minimalist visual style allows a patient to observe healthy limb movements in the non-paretic arm or in example limb movements modelled by the application without the distraction of superfluous imagery employed for aesthetics.

The Nintendo Wii is a low cost option for VR rehabilitation therapy. Its interface is unique among all of the VR rehabilitation systems in that it requires a controller. The current trend in VR gaming therapy is towards motion capture camera technology. As was suggested by Neil et al. [17], Wii use was shown to result in comparatively less intensity of movement and fewer repetitions compared to the motion capture Sony EyeToy. Only the Nintendo Wii requires the patient to wield the extra weight of a controller.

While difficulty is adjustable in the commercial VR systems, gameplay is more modifiable in the rehabilitation specific systems. The rehabilitation VR systems allow more minute adjustments, typically by a PT or OT, in speed, frequency, and distance. The greater malleability of the game performance creates a more tailored experience for the patient and may optimize the therapeutic experience. The RGS system automated this process with the addition of the PTM. The PTM provides the RGS the functionality of adapting its gameplay to the user's performance [9]: it is theorized that the PTM will provide a more satisfying and challenging experience without frustrating the patient with overly difficult tasks. The expected result is an automated VR therapy that optimizes intensity and repetitions. This effect was seen in a steeper improvement curve of upper extremity (UE) function in acute patients with stroke [23]. The PTM is a potentially useful application that should be applied to the commercially available VR gaming systems, which are often played in an unsupervised setting.

Adverse effects were rare among the studies and relatively minor in nature. Joo et al.'s [13] study of the Wii induced lethargy and fatigue in two patients and transient muscle soreness in three others. The only reviewed immersive VR intervention, which incorporated a VR projection helmet, resulted in two of the nine patients reporting short-term dizziness and headache [19].

Conclusion

The VR gaming therapies presented in the literature draw upon the themes of action observation, imitation, versatility, intensity, repetition, and the persistence of functional limb improvements associated with rehabilitation efforts. Researchers should continue to improve upon study rigour while incorporating larger test samples. Standardization of acceptable outcome measures should be a priority of the research community and follow-up testing should be encouraged to support claims on long-term therapeutic effects.

Future research would benefit from more direct comparison between commercial and rehabilitation-specific VR gaming modalities. Specific populations with stroke should be incorporated into those studies as a means of assessing the optimal VR modalities for acute stroke patients with stroke vs the chronic.

Combinations of therapy should be explored. Rehabilitation-specific VR gaming therapies may elicit better results at re-teaching paretic limbs during the more neurologically plastic acute post-stroke phase. Commercial VR gaming therapies may be found to be more adept at motivating patients to continue to use a paretic limb by providing less expensive and more varied and entertaining therapy options.

There is a paucity of statistically significant research attesting to VR rehabilitation's efficacy in producing improvements in hand and wrist function. The latest RGS trial introduced a novel haptic interface consisting of two integrated mechanical arms, which provide sensorimotor feedback when the patient virtually catches a sphere. The post-intervention results for hand and wrist function were favourable. Research into increasing gains in hand and wrist function during UE VR rehabilitation therapy should be given precedence.

Only one recent study was published, which included the integration of a VR headset. Modest gains were seen, but also minor adverse effects. Immersive VR therapies are less prevalent and, although their future role is far from being clear, at least two major commercially available VR headsets, the Oculus Rift and the Sony Morpheus, are in development. It is too early to tell what if any impact these new headsets could have on VR rehabilitation therapy. However, the renewed interest in this technology may stimulate research into VR headset applications.

Rehabilitation VR gaming therapies are not widespread. Most patients with stroke undergo traditional PT and OT in a facility or in their homes. However, VR therapy continues to generate a growing research base, while offering patients the opportunity to exploit entertaining and modifiable environments. As the technology evolves and commercial gaming systems become more ubiquitous, potential opportunities to utilize VR therapy on its own or as an adjunct to traditional therapy will continue to increase.

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Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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