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Virtual reality and serious games in neurorehabilitation of children and adults: Prevention, plasticity and participation

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Introduction

Virtual reality (VR) was developed in the early 1900s through application of in-flight simulations.¹ VR is the generation of simulated or virtual environments (VE) that allow user interactions through multiple sensory (visual, auditory and haptic-sense of touch) channels.¹ Customized VR systems have been designed using specialized hardware, such as haptic robotic interfaces, or off-the-shelf hardware such as the Kinect camera. Specialized VEs are based on enriched environments and designed with principles of motor learning for example, with feedback and task specificity.²

A special characteristic of VR systems is that they create the illusion that a person is interacting with a synthetic world. These states have been defined as presence, immersion and flow. The state of presence, or the experience that the environment is real,³ is created in part by the system's capacity to deliver the illusion of reality or degree of immersion. Hardware used to deliver the VE creates the immersion characterized along a continuum; with highly immersive customized environments using head mounted displays (HMDs) and caves. Caves are room-size visualizations in which multiple users can share the same experience. It is the most immersive with desktop computers or tablets using off-the shelf video games as the least immersive. The degree of immersion is not necessarily related to the effectiveness of the VR system. The interactivity of the VE is important in order to create engagement. The user experience is characterized by attributes of challenge, positive affect, "endurability", aesthetic and sensory appeal, attention, feedback, novelty, interactivity, and perceived user control.⁴ VR and video games create a state of flow, a multi-dimensional construct, describing the user in an optimal performance zone.⁵ For people to sustain intense activity, regarded as central for neuro-rehabilitation, the person's attention and motivation matter. While not the main focus of this paper it is important to realize that the manipulation of the virtual environments, feedback, and the state of the person in the VE are all important considerations for rehabilitation.

Rehabilitation applications of VR emerged for adults then children for the management of pain associated with burns.^{6,7} The term virtual rehabilitation was created at the first Workshop on Virtual Rehabilitation.⁸ The first publications in adult rehabilitation focused on people post-stroke^{9–12} with publications in pediatrics primarily focused on children with cerebral palsy, although children with other disabilities have been studied.¹³ Physical therapists have used both customized VEs and active video games or commercial off-the-shelf games. The active video, off-the-shelf games were developed for recreation but are adapted for rehabilitation and take advantage of the motion sensing features of the games. For this paper we refer to these commercial games, such as Nintendo or Kinect, as serious games (SG) because they were adapted for a purpose other than entertainment. Studies of rehabilitation have incorporated the games as safe, motivating, engaging, and fun task-specific practice to facilitate restoration of movement capabilities.^{2,14,15} Customized lab based systems in parallel with SGs have been explored for their potential to motivate and provide meaningful intensive repetitive practice in ecologically valid environments.^{2,13,16,17,18}

Prevention

VR and SG offer an engaging and affordable way to encourage and increase physical activity. VR and SG as a secondary prevention intervention to increase fitness and decrease obesity and the related health risks in children with neuromotor conditions began in 2006. Widman et al.¹⁹ demonstrated that 8 children with spina bifida could increase their energy expenditure to a moderate level while arm cycling within a VE. More recently, Fehlings et al.¹⁴ reported on four studies^{20,21,22,23} enrolling 52 children with cerebral palsy (CP) utilizing Wii Sports, DanceDanceRevolution, Sony Playstation Eye Toy, a robot for ankle impairments, and an internet mediated interactive motor and cognitive training program. The VR or SG dose prescribed within these studies varied. Common outcomes reported were the metabolic equivalent for tasks (METs) and the 6-minute walk test (6MWT) with varied improvements reported. Most participants did show moderate energy expenditure with some children reaching vigorous levels, however the 6MWT results were conflicting between studies. More recently Robert et al.²⁴ measured energy expenditure in 10 children with CP playing Wii games and also found children could reach moderate levels of energy expenditure. Similar findings were reported for children with autism.²⁵ The length of time spent at a higher intensity of physical activity could be increased with use of VR and SG.

For adults with neurological conditions direct evidence for use of VR in a secondary and tertiary prevention model is sparse. The research exists primarily in the form of modifying risk factors for falls. Reducing fall risk has been reported both in studies for people with Parkinson Disease (PD)²⁶ and people with Multiple Sclerosis (MS).²⁷ There is work with active video games for wellness fitness for prevention.

There are several research groups who have reported energy expenditure of people post-stroke while playing Wii²⁸ and Wii and Kinect games.^{29,30} There is a hierarchy for energy expenditure with standing balance games having the lowest requirements and standing activities that involved the upper limb, such as boxing with the largest expenditure. People, post-stroke worked in the lower end of the moderate range, which was comparable to over-

ground walking. The games therefore may be suitable for wellness, but are not intense enough for fitness.

One of the limitations to increasing energy expenditure is that the exercise takes place in an environment where the movement type and intensity is self-selected. It is possible that coupling video games as well as VEs with a closed system such as bicycling may address this limitation. Pilot work with a “sensorized” bicycle yoked to a virtual cycling environment³¹ supported that people post-stroke could train for up to an hour, two times a week over a period of eight weeks and improve their VO₂ as well as their gait speed.³² For people with PD, a cycling VE embedded with cueing and feedback increases cycling speed.³³ VEs coupled with bicycles may augment the existing cycling programs used to improve fitness for people with PD.^{34,35} Similar improvements in fitness have been shown with VR arm and leg cycling systems in children with CP.^{19,36} While these studies are promising for secondary prevention, larger and longitudinal evaluations of the effects of active VR and SG on wellness or health and fitness are necessary to demonstrate efficacy, determine dose, and document prevention of future health problems. Health and wellness outcomes after VR should be compared to active physical exercise in the natural environment.

Outcomes of VR and SG Interventions

VR and SG offer the potential of practice in VEs that simulate natural environments yet allow for safer practice by individuals with neuromotor disorders. The majority of studies of adults and children reported body function/structure and activity outcomes, whereas only a few reported participation outcomes. We have included a brief review of intervention studies of children and adults with outcomes across these International Classification of Function (ICF) domains.

Studies with Children as Participants

VR and SG applications for children include the use of SG and customized systems for specific motor practice.¹⁵ Outcomes varied in the ICF domains, with most measurements related to body structure and function and overall gross or fine motor activity. Some studies focused on sensory impairments including visual spatial training³⁷ and sensory attention for balance,³⁸ and some focused on intensity of exercise for improving fitness.^{19–25} Children with CP have been the most common participants,^{20–24,36,37,39–72,23,73–79} however there are several studies with children with Down syndrome,^{80,81} developmental coordination disorder,^{82,83} autistic spectrum disorder,²⁵ muscular dystrophy,^{46,51} and spina bifida.¹⁹ Studies are underway for children with acquired brain injury.⁸⁴ The primary VR and SG systems used in the studies are the Wii Fit, Sports, and Balance systems. Many specialized systems have been developed for both upper^{43,45,47,56,59,60,69,72} and lower^{23,36,41,76} extremity applications as well as greater motor control.^{41,76,82} Improvements in postural control have been studied primarily with use of the Wii and Kinect systems.^{53,54,57,63,}

Body Structure/Function and Activity Domains

Twelve published systematic reviews that focused on VR and SG intervention included nine that reported motor outcomes.^{13,86,87,14,88,15,89, 85,90} The nine systematic reviews were completed between 2009–2015 and varied in focus. (Table 1) Within the reviews, there were 12 randomized controlled trials (RCT) and 85 other types of intervention studies suggesting a relatively large amount of research on VR and SG in pediatrics. Each review, however, suggested that the overall design quality of the research studies was low, level 2b through 5 on the Center for Evidence Based Medicine (CEBM) scale.⁹¹ Children age 4–20 years participated in these studies, including 776 children with neuromotor conditions. Seventy percent of the participants were children with CP with the remaining participants having Down syndrome and coordination disorders. The recommended VR or SG dose, was between 1–70 hours (mean 15 hours sd 12; median and mode 9 hours). Improvements in body structure/function included balance, range of motion, strength, coordination, and kinematics with activity domain outcomes improving in some studies and not in others.

Two recent RCTs and two non-randomized clinical trials, not included in the above reviews^{18,92–94} compared VR and SG interventions to control conditions with children with CP^{18,92,93} and children with Fetal Alcohol Spectrum Disorder (FASD) who had motor disabilities.⁹⁴ Mixed results for children with CP using MiTii exercise are reported. One group reported statistically but not clinically significant higher performance with MiTii than the standard care group. Whereas Lorentzen et al.,⁹² who used double the dose of the previous study, reported a large training effect for changes in gross and fine motor activity as compared to a group who received no intervention. Tarakci et al.¹²⁶ reported similar findings for children with CP as per the previous reviews with positive improvements on balance outcomes after use of the Wii Balance system. Jirikowic et al.⁹⁴ evaluated a customized game based VR system delivered through a HMD (Sensorimotor Training to Affect Balance Engagement and Learning, STABEL) to provoke practice of standing balance in a sensory environment designed to require a shift of sensory attention from vision and somatosensation to vestibular sensation to maintain balance. Statistically and clinically significant improvements in both balance and overall motor ability after 4 hours of intervention were reported in the intervention but not the control group who received no intervention. These recent results are similar to the earlier research with generally positive improvements in body structure/function domain but mixed results in activity domain outcomes.

Participation Domain

Eight pediatric studies have measured a participation outcome. Five used the Canadian Occupational Performance Measures, which includes the collaborative creation of individualized goals,^{18,59,70,95,96} one study used the Test of Playfulness⁵⁸ and two used the Assessment of Motor and Process Skills.^{18,92} Most studies indicated a positive improvement in participation. However two^{96,97} indicated that the differences between the VR and SG system and standard care groups were not clinically significant.

Adults as Participants

The use of VR and video games for adults with neurological conditions can be grouped into enhancement of upper limb (UL) use, balance and mobility training, sometimes termed lower limb training, Activities of Daily Living (ADLs), neglect and cognition. We report on movement outcomes for people with stroke, PD and MS but not ADLs, neglect or cognition.

Body Structure/Function and Activity Domains

The largest body of work is with people post-stroke reflected by a 2015 Cochrane review that was updated through July of 2014 and is currently being revised for a third time.⁹⁸ Since the Cochrane review there are six systematic reviews with meta-analyses on balance and mobility.^{99–102,103,104} These reviews (Table 2) have different objectives including the evidence on the Wii,⁹⁹ discriminating between VR coupled with treadmills, customized systems that do not involve a treadmill and off-the-shelf games.¹⁰³ There is a small but consistent benefit for VR in gait measured by gait speed,^{100,102–104} and balance measured by the Berg Balance Scale (BBS) and the Timed Up and Go (TUG).^{100–104} The meta-analyses favor VR with balance outcomes, however, these studies do not meet the minimal clinically important difference (MCID).

Three systematic reviews synthesize the work on use of VR-based activities for the UL post-stroke^{98,105,106} The early studies reviewed by Saposnik, were primarily single group studies that measured body structure/function and activity level outcomes. VR improved UL function for people in the chronic phase post-stroke.¹⁰⁶ The review by Lohse considered serious games and VEs and described support for an additive effect for serious games and VR based activities over traditionally presented UL rehabilitation activities.¹⁰⁵ The most detailed analysis was provided by Laver et. al., in the Cochrane review⁹⁸ and support that VR augmented therapy for the UL enhances UL use. People in the acute phase post-stroke fare better than those in the chronic phase and the dose of intervention matters. People who received more than 15 hours of intervention improved more than those who received less than fifteen. Taken together these studies show a steady progression of support to incorporate VR into UL interventions for people post-stroke. Innovation and optimization of these therapies is underway with the advent of smaller sensing devices as well as less intrusive and less expensive UL supports.

For people with MS there are a combination of SG used for rehabilitation, primarily the Wii and treadmills coupled with VEs. Taylor and Griffin published a narrative systematic review of 11 studies and one protocol using gaming technology, both the Wii and the Kinect, for rehabilitation of people with MS.¹⁰⁷ They reported that use of Wii Fit games in a clinical setting yielded improvements in postural control¹⁰⁸ as well as functional balance.^{109,27,110} One group of investigators designed a dynamic platform that was coupled with the Wii games. This created a more dynamic balance challenge than using the Wii platform alone, which did not result in improved postural control or functional balance.¹¹⁰ Feasibility of a telerehabilitation model was tested and demonstrated improvements in activity-based balance measures for both the local group as well as the remote group using Kinect. The remote group had postural control improvements, which the control group did not.¹¹¹ A walking study, coupling VR with a treadmill, produced gait and dual task balance improvements.¹¹²

Overall there is a small body of work with studies at level 2b to 5 on the Center for Evidence Based Medicine (CEBM) scale.⁹¹

For people with PD the literature has been summarized (Table 3) with narrative reviews on assessment and treatment of balance and gait using VR¹¹³ and exergaming (use of video games for physical activity).¹¹⁴ Nine studies used either the Sony Playstation¹¹⁵ the Wii^{116–121} a customized balance board¹²² or a treadmill VR combination.²⁶ The findings generally have activity-based outcomes that favor VR. More recently investigators have used the Kinect to develop customized applications for balance training¹²³ and reported preliminary positive balance findings in a cohort study. Another study suggested no difference when comparing home-based therapy to home based VR therapy.¹²⁴ In a study with dancing (with the K Pop Dance Festival from the Wii) added to the standard of care, participants had reduced symptoms of depression and improved balance.¹²⁵ The results of the largest multi-center clinical trial on walking with VR, VTIME, are pending.¹²⁶

Across all the populations studied researchers have examined SGs, predominantly the Wii (although newer studies are reporting use of the Kinect), customized balance systems and treadmills yoked to VR and UL robotic interfaces connected to VR. Research has evolved to more dose matched studies of higher quality. The highest levels of evidence are for studies on UL use and balance and mobility training for people post-stroke. There is a lag between commercial video game development and application to practice as evidenced by very few studies using the Kinect.

Participation Domain

Measures of participation were absent from all the systematic reviews on balance and mobility of people post-stroke with the exception of Mirelman et al¹²⁷ who measured improvements in ambulation in the community for 1 week prior to and 1 week after the conclusion of the VR intervention. For the UL studies in people post-stroke the Stroke Impact Scale is reported as a participation measures in only two studies.^{106,128} By contrast, in a review article on use of Wii for rehabilitation of people with MS participation measures were included in three out of the 9 RCTs or cohort studies.¹⁰⁷ A study protocol¹²⁹ included measures of participation. Participation outcomes improved on measures such as the Physical Activity and Disability Survey, the SF-36, the Multiple Sclerosis Fatigue Impact Scale^{27,130} and the Multiple Sclerosis Impact Scale.¹⁰⁹

For people with PD change in participation was reported based on scores on the Parkinson Disease Questionnaire (PDQ) in two cohort studies and one RCT.^{121,116,131} People with PD who were on average 5 years post-diagnosis played Wii Sports (specifically tennis, boxing and bowling) for 12 one hour sessions over one month and improved in the PDQ that lasted four months post intervention.¹²¹ Changes in the PDQ were reported by a group that used the Wii as a balance training tool¹³¹ and similarly by a group that used the Kinect Adventures games to improve balance.¹¹⁶ By contrast a home-based VR intervention for balance and mobility was no different than standard of care home physical therapy in changing the PDQ.¹²⁴ The frequency with which participation is used as an outcome in studies of people post-stroke was lower than that reported for people with PD or MS. This

may in part be explained because of the progressive nature of MS and PD and the belief that participation may be altered but body structure/function may not.

Plasticity

Plasticity is a complex cellular and molecular process depending on genetic, epi-genetic, environment, and activity conditions.^{132–135} VR and SG interventions potentially offer a method to promote meaningful, through engagement and flow, repetitions of movements in order to change brain structures. Noninvasive measurement of brain changes, however, is complex and little data are available related to either pediatric or adult VR and SG interventions. This is partially due to the relative discomfort and difficulty remaining still for brain scans, especially for children, and the cost of the scans. Other issues relate to the variability of neural activity between individuals, reliability and sensitivity of brain scan results in children, and lower relationships between magnetic resonance imaging (MRI) results and motor ability.¹³⁶

Two studies of children with hemiplegic CP (n=4) evaluated for brain changes after VR and SG interventions. Functional MRI findings from one participant in the You et al.,⁷² study suggest that IREX, a computer interaction with sensor gloves intervention, influenced greater contralateral control of the child's affected arm. Golomb et al.,⁴⁷ utilizing a sensor glove and the PlayStation 3 system found expanded activation of the primary motor cortex and cerebellum and greater contralateral activation. Two studies^{84,137} with larger numbers of participants are ongoing that include brain scans in children with acquired brain injury and CP.

Five studies of adults with neurologic conditions have evaluated use dependent plasticity associated with learning. Two early studies of people post-stroke reported functional improvements in UL use and gait that paralleled a shift from contralesional sensorimotor activation pre-therapy to predominantly ipsi-lesional activation post-therapy.^{138,139} More recently, Saleh et al.,¹⁴⁰ reported changes in connectivity between the lesioned and non-lesioned hemisphere with one subject demonstrating increases and the other subject decreases in the lesioned hemisphere. In contrast, Orihuela et al.,¹⁴¹ reported contralesional activation of the unaffected motor cortex as well as cerebellar recruitment and compensatory pre-frontal activation. These studies included participants in the chronic phase post-stroke and the total number was less than 20, thus, the findings are limited. The remaining two studies included participants with MS. Prosperini reported balance improvements after a 12 week training program with the Wii that were associated with increased structural integrity of the superior cerebellar peduncle.¹⁴² Cognitive based video games reporting experience-dependent plasticity are not included in this paper.

Short-term plasticity has been demonstrated with VR manipulations of visual representations. Using the phenomenon of visuomotor discordance, that is reconciling the discrepancy between intended actions and discrepant visual feedback, investigators have shown that motor area (M1) activation is increased as healthy adults try to reconcile this discrepancy.¹⁴³ This manipulation may result in use dependent plasticity and more permanent structural changes.

The use of brain scans within pediatric and adult practice could add significantly to the understanding of the baseline neurological problems of individuals with neuromotor conditions and also could provide guidance for evaluating and adjusting intervention programs that use VEs.¹⁴⁴ Scanning could potentially determine neurological reorganization and assist with understanding restoration versus compensation.

Bridging the Gap from Evidence to Practice

VEs and SG have appealed to practitioners and participants. Transferring the technology to the clinic and home and the knowledge to implement technologies remain a challenge. VR systems were customized in a lab and not available for purchase. With the wide availability of VR through motion-controlled games such as Wii and Kinect the technology has become more accessible and clinicians have indicated willingness to adopt them in practice.¹⁴⁵ However, barriers exist to implementing these technologies in clinical practice. Lack of knowledge about the VR systems, and time to implement them into practice are barriers. There are concerns that the variety of games make it difficult to find the best exercise to meet a person's needs and may shift the person's attention from the movement practice itself to the game play, which may degrade the movement practice.¹⁴⁶ We offer suggestions for education, practice and research that may enhance informed adoption of the technology.

Education

Education may take the form of continuing education for clinicians and formative education for students in training.¹⁴⁵ Researchers suggest that training should result in students and therapists being able to problem-solve the active ingredients within various VE and VR or SG systems and utilize the systems to their clients' advantage.¹⁴⁵

For students at entry to the profession, we suggest that selecting the correct technology and application is an extension of clinical reasoning that may be best taught in a distributed model across classes rather than as a unit in one class. Specific suggestions include students learning to evaluate the evidence supporting the technology as well as practicing the implementation of the technologies as tools for therapeutic exercise and movement re-education on themselves and through integrated clinical experiences prior to their clinical internships. Practicing therapists should consider the VR and SG systems as one more addition to their intervention toolbox that should be systematically analyzed and applied judiciously.

Resources for clinicians and educators

Although clinicians were enthusiastic with the introduction of VR and SG in practice there are challenges with understanding the content and application of the systems. Early publications incorporating SG into practice aimed to describe the games as well as the rationale for selecting them for a specific practice application.^{44,147} Galvin and Levac suggested a method for consideration of VR and SG systems for pediatric rehabilitation that may generalize to adult rehabilitation.¹⁴⁷ They created an algorithm for selection of the most appropriate system based on an analysis of system variables including ability to manipulate, track, target body movements, adjust motor demand, and focus on quality of movement and

user variables such as upper and lower limb requirements to play the game. With this system, students and therapists can consider the intensity of physical activity, the nature of movement, amount and frequency of active movement and adjustment to the therapeutic goals for the client. Levac and Galvin offer case examples of using the classification system for decisions about VR and SG systems for children.¹⁴⁸

There have been efforts to analyze the Wii and Wii Fit games that are bundled with the console and balance board for ease of use and practice.¹⁴⁹ This game analysis identified game applications for rehabilitation of balance, strength, endurance and it extracted both the knowledge of results (KR) and knowledge of performance (KP) information. The games provided more KR and positive feedback than KP. Clinicians need to be mindful of the movement strategies clients use while playing the games. More recently, five investigators have collaborated on a game analysis of the Kinect Adventure Games.¹⁵⁰ The Kinecting with Clinicians (Kwic) resource is used on-line with cases and videos (<http://kinectingwithclinicians.com/>). This on-line resource illustrates with case studies the implementation of video games into the rehabilitation for children and adults. The authors have created descriptions of the games using motor learning definitions and practice terminology. Studies are underway to determine its usefulness and whether it is scalable and sustainable.

Linking clinicians and researchers

While the SG systems are appealing because of their low cost, they are limited by the lack of customization and rehabilitation-relevant theoretical framework that informs their design. Customized systems are superior to SG in balance and mobility studies in people post-stroke and with upper extremity function in children with CP.^{89,103} One problem with these customized systems is that many are developed and tested and then discarded because no method exists to transfer them out of the lab and into the clinic. To address this gap, clinician scientists and engineers from Spain, Portugal and the US have created an online resource, Open Rehabilitation Initiative, to share executable versions of the VR and SGs.¹⁵¹ This resource was tested by clinicians, VR and robotic developers and awaits the next phase of development which is soliciting and posting simulations. The creators hope that this forum allows clinicians to inform the development of the technology and use it. For contribution to or tracking the development of this site readers can contact openrehabinitiative@gmail.com.

Reflections and Recommendations

Virtual Reality is a rapidly developing area with advances in technology that often outpace the research. Evidence is accumulating to support the use of VR and SGs either alone or in addition to standard of care. The body of evidence remains confounded by the challenge of parsing the customized lab based simulations with the off-the-shelf games and the hybrid systems that use off-the-shelf hardware with customized software. As the development, research, knowledge translation and application move forward, physical therapists play an integral role in shaping the process. Physical therapists are currently involved in all aspects

and can influence the types of technologies that are developed for their clients by contributing to development as well as application.

Prevention, plasticity, and participation effects of VR and SG are under-studied. Larger numbers of participants are needed for prevention studies and the studies need to be directed at primary as well as secondary and tertiary prevention. Evaluations of brain changes through the process of plasticity from VR and SG intervention depend to a great extent on the brain scanning technology and cost of these services. Research investigating recovery in more acute stages post nervous system insult could guide use of VR and SG. Most of the research on VR and SG has been done at the body structure/function and activity domain particularly in studies of balance and locomotion. For chronic adult conditions such as PD and MS, participation is more regularly documented. In the pediatric literature there are reports including participation outcomes, based on individualized client goals as measured with the COPM, but participation is not included in the majority of studies. The COPM customizes goals, which can be directed towards participation. This tool may be well suited across a variety of populations. Due to some conflicting evidence on carryover of motor improvements within VR systems to the natural environment, future research on participation outcomes should also evaluate VR and SG practice alone and within natural environments to determine programs leading to the best movement outcomes.^{100,127,131,132} Standardization of behavioral outcome measures across studies would increase the usefulness of meta-analyses. Control interventions should be standardized and described in addition to the VR and SG programs.

If these technologies are to be used in practice, a synergy between commercial entities, researchers, educators, clinicians and clients needs to occur. We advocate for partnering of communities through professional organizations such as the American Physical Therapy Association, Academies of Neurology and Pediatric Physical Therapy, the International Society of Virtual Reality, International Industry Society in Advanced Rehabilitation Technology and interested academic and industry partners to standardize technology development and research. This work should be guided by a patient centered approach to achieve the goal of clinical application of VR/VE and SG to improve movement, function, and participation in clients with neuromotor conditions.

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Table 1
Summary of Current Systematic Reviews of VR, VE and SG Research in Pediatrics*

Authors (year)	Purpose & participants	N participants (# studies reviewed)*	VE/VR-SG	BS/F outcomes (+;+/-;-;-)	Activity outcomes (+;+/-;-;-)	Participation outcomes (+;+/-;-;-)
Sandlund et al. (2009)	To determine effectiveness of application of interactive computer play in rehabilitation of children with sensorimotor disorders	245 (16)	Gesture-Tek (IREX, Mandala Gesture Xtreme), sensory glove, Eye-Tek, Interactive metronome, Other custom system	fMRI + Sensory profile +/- Kinematics +/- Arm motor control + Spatial orientation +/- Motivation +	BOTMP +/- M-ABC - QUEST +/- PDMS-2 +/- Line tracing +	COPM +/- ToP +
Galvin et al. (2011)	To determine effectiveness of VR to improve upper limb function in children with neurological impairment	32 (5)	Eye-Toy-Play, IREX, PITTS, Gesture-Tek Extreme	Kinematics + Accuracy + Visual motor +	BOTMP +/- QUEST +/- MAULF + BBT + 9-hole peg test + PDMS-2 +	COPM +/-
Mitchell et al. (2012)	To determine effectiveness of VR on physical activity capacity & Performance in children with early brain injuries (TBI/ABI) including CP	28 (4)	Mitii, Wii, IREX, SonyPlay Station	Isometric Strength +/- Functional strength + Time over 3 METs +/- 1MWT -	Physical activity (steps) + TUDS + 6MWT +/-	
Fehlings et al. (2013)	To determine effectiveness of interactive computer play (ICP) to improve motor performance (including motor control, strength, or cardiovascular [CVS] fitness) in individuals with cerebral palsy	364 (24)	Nintendo Wii Sports or Fit, Mitii, EyeToy for Sony PlayStation, VE +CIMIT, VE+Cycling, VE +Treadmill, other custom system	UE Kinematics + Active ROM + Muscle activation + Movement speed + Movement accuracy - LE Ankle ROM + Joint stiffness + Dorsiflexion strength +/- SCALE + Balance +/- PBS + Gait steadiness + Gait symmetry + Treadmill speed + Functional strength + Cardio VO ² + 6MWT +/- Bruce treadmill test + METs + Total energy expenditure +	UE Function +/- Melbourne +/- QUEST - MAULF +/- Reaching + AHA - MABC-2 + BOTMP-UE +/- MACS LE SWOC + GMFM + MABC-2 + BOTMP - SACND + Cardio Number of steps + Time spent in activity +	COPM +/- AMPS + Level of Participation +

Authors (year)	Purpose & participants	N participants (# studies reviewed)*	VE/VR-SG	BS/F outcomes (+, +/,-, -)	Activity outcomes (+, +/,-, -)	Participation outcomes (+, +/,-, -)
LeBlanc et al. (2013)	To explain the relationship between AVGs and nine health and behavioural indicators in the pediatric population (CP, DS, Autism)	161 (9) (only studies for children with neuromotor conditions reported)	Wii, DDR, Kinect	VIM + TVMI + TSIF + Time in MVPA + Correct responses on VR game + Max work capacity +	MAULF + BOTMP + Functional mobility +	
Monge Pereira et al. (2014)	To determine the impact of the use of VR systems in the improvement and acquisition of functional skills in children with CP	97 (13)	Wii, IREX, EyeToy, other custom system	Postural tone + Postural alignment + Proximal stability + Balance + Coordination + Quality UE movement + Bone health + fMRI + IMWT - Gait speed and stride length + Knee joint torque + sEMG faster activation +	SACND +/- QUEST - Active function + MABC 2 + BOTMP - Steps/meter travelled +	COPM-
Chen et al. (2014)	To determine the effect of VR on UE function in children with CP	125 (14)	EyeToy, Gesture Extreme, Wii, Ultra-glove, other custom system		PDMS-2 (UE) + BOTMP -/+ JB - ABILHAND + CHEK + MAULF +/- QUEST +/- SHUEE +/- PMAL + BBT -	COPM +/-
Bonnechere et al. (2014)	To determine the use of SG in rehabilitation in children with CP	419 (31)	Wii, Miti, VE +Cycling, EyeToy, Kinect, other custom system	Benton Judgment of Line + Orientation test + Arrows subtest of the Nepsy +, Roads test + SPPC + Strength + PBS + Bone mineral density + Knee muscle torque + Pediatric Volitional Questionnaire (motivation) + Reaching kinematics + fMRI + ROM + Borg Scale of Perceived Exertion + Total energy expenditure + Number of steps + Time spend to play +	Computer based and non-computer based games - QUEST - BOTMP -/+ MACS - Reaching task + GMFM - Fine motor + TUG BBT + JT + ABILHAND-Kids + TUDS - MAULF -/+ PMAL + FMA (UE) + Functional mobility + Hand function +	COPM +/- Participation + ToP + questionnaire on engagement and participation +

Authors (year)	Purpose & participants	N participants (# studies reviewed)*	VE/VR-SG	BS/F outcomes (+;+/-;-;-)	Activity outcomes (+;+/-;-;-)	Participation outcomes (+;+/-;-;-)
Dewar et al. (2015)	to evaluate the efficacy and effectiveness of exercise interventions to improve postural control in children with CP	34 (3)	Wii, IREX	MAS – MTS – SCALE + 6MWT + Balance –/+ Gait speed + Heart rate + fMRI – Visual Perceptual Skills + Posture Scale Analyzer + Number of correct movements + Forearm bone density + Pelvic ROM + Trunk control +	BOTMP – TUDS – GMFM –	

* Within the systematic reviews there was repetition of some articles, with 62 original studies included overall among all reviews.

+ supporting evidence; +/- inconclusive evidence; – no change/no difference

VR/VE and SG systems abbreviations: Interactive Rehabilitation Exercise System (IREX); (PITTS); Constraint Induced Movement Therapy (CMIT); Dance Dance Revolution (DDR); Virtual reality (VR); Virtual environment (VE); serious games (SG)

Assessments abbreviations: Functional Magnetic Resonance Imaging (fMRI); Bruininks-Oseretsky Test of Motor Performance (BOTMP); Quality of Upper Extremity Skills Test (QUEST); Movement Assessment Battery for Children-2 (MABC-2); Peabody Developmental Motor Test – 2nd Ed (PDMS-2); Canadian Occupational Performance Measure (COPM); Test of Playfulness (ToP); Melbourne Assessment of Unilateral Upper Limb Function (MAULF); Box and Blocks Test (BBT); Timed Up and Down Stairs (TUDS); 1-minute walk test (1MWT); 6-minute walk test (6MWT); Range of motion (ROM); Assessment of Motor and Process Skills (AMPS); Assisting Hand Assessment (AHA); Manual Ability Classification System (MACS); (UE); Selective control assessment of lower extremities (SCALE); Standardized Walking Obstacle Course (SWOC); Pediatric Balance Scale (PBS); Sitting Assessment for Children with Neuromotor Dysfunction (SACND); Maximum volume of Oxygen (VO_2^2); Metabolic Equivalent of Task (MET); Visual Motor Integration test (VMI); Developmental Test of Visual Motor Integration (TVMI); Test of Sensory Integration Function (TSIF); Moderate to Vigorous Physical Activity (MVPA); Surface Electromyography (sEMG); Jebsen-Taylor Hand Function Test (JTHF); ABILHAND; Children's Hand Use Experience Questionnaire (CHEK); Shriner's Hospital Upper Extremity Evaluation (SHUEE); Pediatric Motor Activity Log (PMAL); Gross Motor Function Measure (66 or 88 items) (GMFM); Timed up and go (TUG); Fugl-Meyer Assessment (FMA); Modified Ashworth Scale (MAS); (MTS); Self-Perception Profile for children (SPPC); Community Balance and Mobility Scale (CBMS)

* A search of the literature was completed within PubMed in June 2016 limited by age (birth -18 years), English language, and the search words of Bonnechere et al.⁸⁵ (serious gaming, serious games, virtual reality, tele-rehabilitation, virtual environment, computer game, exergaming) and additionally “interactive computer play”, all with “rehabilitation.”

Table 2
Summary of Systematic Reviews of VR and SG for Balance and Mobility of Persons Post-Stroke

Author	Purpose	N	VR-SG	Body Function Structure	Activity	Participation
Cheok et al (2015) July 2014	Use of Wii For Stroke Rehab	170 (6)*	Nintendo Wii	Postural Control +/-	WMFT + BBS +/- FIM +/-	SIS +/-
Corbetta et al (2015) Aug 2014	VR for Balance and Walking Post-Stroke	341 (15)	Treadmill + VR Nintendo Wii Customized VR	Kinematics Postural Control FM	Gait Speed + ^F TUG + BI FRT 10MWT	Community Ambulation + FIM ABC
Li et al (2015) May 2015	VR for balance + gait in post-stroke	428 (16)	Treadmill + VR Nintendo Wii Customized VR	Postural Control +/- Temporal Spatial +/-	BBS + FRT +/-	TUG + ABC +/-
Gibbons et al (2016) August 2015	VR for LL outcomes post-stroke	522 (22)	Treadmill + VR Nintendo Wii Customized VR	Postural Control + Temporal spatial + MMAS + Tardieu + FM +/- Ashworth + Chedoke +/-	BBS + Gait Speed + 6MWT + ABC +/-	FRT+ TUG + WAQ + DGI +/-
Iruthayarajah et al (2016) Sept 2015	VR for balance + gait for chronic stroke	984 (20)	Nintendo Wii Fit Treadmill +VR Postural VR	Postural Control +/- Activity	BBS + FRT +/- 6MWT +/- Tinetti +/-	TUG + 10MWT +BBA +/-
DeRoosj et al Dec 2015	VR for gait and balance post-stroke w/matched dosing	(21)	Treadmill + VR Balance board	Temporal spatial +/- Postural control + Activity	Gait speed + 10 MWT +/- FRT + Tinetti +/-	BBS + TUG + BBA +/-

VR Virtual reality, SG Serious Games, WMFT: Wolf Motor Function Test, TUG: Timed Up and Go, BBS: Berg Balance Scale, FAC: Functional Ambulation Capacity, FIM: Functional Independence Measure, BBT: Box and Blocks Test, SIS: Stroke Impact Scale, FM: Fugle Meyer, 6MWT: Six minute walk test, BI: Barthel Index, FRT: Functional Reach Test, ABC: Activity Based Confidence Questionnaire, 10MWT: Ten meter walk test, MMAS: Modified Motor Assessment Scale, WAQ: Walk Activity Questionnaire, DGI: Dynamic Gait Index, BBA:

* half the studies were dose matched, included UL and LL studies,,

+favor VR and – favor control

Systematic reviews of the literature on VR and SG for adults were searched on PubMed (published by June 2016) using the following terms, virtual reality, virtual environments, video games, serious games, Wii, Kinect, and specific conditions Stroke, PD, MS. These populations were selected because of they represent people that are seen frequently by physical therapists and the corresponding VR literature is sufficiently valid to have been summarized in systematic reviews.

Table 3

Summary of Reviews on VR and SG for Persons with Parkinson Disease

Author	Purpose	N	VR-SG	BFS	Activity	Participation
Mirelman et al (2013) July 2013	VR & MI for balance and gait in Parkinson's	645 (16)	Motor Imagery VR Treadmill + VR Nintendo Wii	Kinematics +/- Postural control +	Stride length + Step latency +/- Gait speed + UPDRS +/-	FRT + TUG +
Barry et al (2014) December 2013	VR's effectiveness in Parkinson's	102 (7)	Nintendo Wii Playstation Eye Toy	MoCA +/-	UPDRS +/- BBS +/- SLS +/-	
Taylor & Griffin (2015)	VR effectiveness in Multiple Sclerosis	298 (12)	Nintendo Wii Xbox Kinect	Postural Control +/- Kinematics +/- SOT +/- SF-36 +/-	TUG +/- SLS + FSST + 4 square + 25-FWT +	BBS + FRT + DGI +/- ABC +/- MSWS-12 +
						MSIS + MFIS +/- Adherence

VR Virtual reality, MI: Motor Imagery, FRT functional reach test, TUG Timed Up and Go, UPDRS: Unified Parkinson Disease Rating Scale MoCA: Montreal Cognitive Assessment, BBS: Berg Balance Scale, SLS: Simple Limb Stance, SOT: Sensory Integration Test, FSST: Four Square Step Test, DGI Dynamic Gait Index, ABC: Activity Balance Confidence Questionnaire, 25-FWT, MSWS-12: Multiple Sclerosis Walking Scale, MSIS: Multiple Sclerosis Impact Scale, MFIS: Modified Fatigue Impact Scale + indicates favored VR, - indicates it favors control