Applied Ergonomics 69 (2018) 153–161

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Review article

Immersion of virtual reality for rehabilitation - Review

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ARTICLE INFO

Keywords:
Haptic feedback
Rehabilitation
Virtual reality

ABSTRACT

Virtual reality (VR) shows promise in the application of healthcare and because it presents patients an immersive, often entertaining, approach to accomplish the goal of improvement in performance. Eighteen studies were reviewed to understand human performance and health outcomes after utilizing VR rehabilitation systems. We aimed to understand: (1) the influence of immersion in VR performance and health outcomes; (2) the relationship between enjoyment and potential patient adherence to VR rehabilitation routine; and (3) the influence of haptic feedback on performance in VR. Performance measures including postural stability, navigation task performance, and joint mobility showed varying relations to immersion. Limited data did not allow a solid conclusion between enjoyment and adherence, but patient enjoyment and willingness to participate were reported in care plans that incorporates VR. Finally, different haptic devices such as gloves and controllers provided both strengths and weakness in areas such movement velocity, movement accuracy, and path efficiency.

1. Introduction

Musculoskeletal impairments are debilitating conditions and they interfere with the normal activities of daily living. According to the National Health Interview Survey (NHIS, 2015), musculoskeletal impairments negatively affect approximately 40% of the United States population (Katz, 2015). Some known disorders and disease that affect the musculoskeletal performance include chronic joint pain (Anderson et al., 1999), arthritis (Reginster, 2002), Parkinson's disease, Guillain-Barré syndrome, and cerebral palsy (Graham and Selber, 2003). The sensorimotor system, which involves the sensory, motor, and integration in maintaining joint homeostasis during bodily movements (Riemann and Lephart, 2002). There are observed associations between these musculoskeletal impairments and the sensorimotor system, the integration structure of sensory and motor processing elements during functional movements (Cioni et al., 1997). Rehabilitation and physical therapy have been the approach to improve the sensorimotor system and musculoskeletal health but often face issues with user adherence (Bassett and Prapavessis, 2007). Besides adherence challenges during the rehabilitation process, the annual expenses attempting to resolve cases of nonadherence could be around $300 billion (DiMatteo, 2004). It is important to address the challenges in existing rehabilitation paradigm to better the outcomes of musculoskeletal health interventions.

Recent research has explored the potential of using virtual reality (VR) as a mode of healthcare intervention and an alternative route for care delivery (Mantovani et al., 2003; Simone et al., 2006). Virtual reality is a computer generated graphical environment that offers opportunities for users to view and interact with the virtual environment in stereoscope (i.e., three-dimensional visuals). In interventions for physical impairments, VR has been proposed and utilized as an assistive rehabilitation technology for individuals suffering from stroke (Jack et al., 2001), cerebral palsy (Reid, 2002), severe burns (Haik et al., 2006), Parkinson's disease (Mirelman et al., 2010), Guillain-Barré syndrome (Albiol-Pérez et al., 2015), and multiple sclerosis (Fulk, 2005) among others. Supported by positive outcomes, Reid (2002) demonstrated improvement in children suffering cerebral palsy of both perceived performance abilities and satisfaction with performance when using VR as a tool for motor training. Using VR as a tool for healthcare may have enhanced ecological validity, real-time performance feedback, interface modification contingency, flexibility, as well as a safer practicing and training environment (Rizzo and Kim, 2005). VR also offers the ability to customize treatment needs while delivering increased adjustment of assessment and training procedures (Sveistrup, 2004).

Some recognized characteristics of VR that make interventions in healthcare advantageous include immersion and engagement in interactivity. Immersion describes the degree of which VR systems are able

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https://doi.org/10.1016/j.apergo.2018.01.009
Received 28 February 2017; Received in revised form 10 January 2018; Accepted 21 January 2018
Available online 06 February 2018
0003-6870/

Table 1
Types of VR systems.

	Non-Immersive	Semi-Immersive	Fully Immersive
Viewing Mediums	Computer monitor, TV screen	Panoramic TV	Head mounted display (HMD), CAVE
Cost	Low	Medium	From low (HMD) to high (CAVE)
Sense of Immersion	Low	Medium-High	High

to deliver experiences that are extensive (i.e., multimodality sensory stimuli), surrounding (i.e., omnidirectional stimuli), inclusive (i.e., no external stimuli from the physical environment), vivid (i.e., richness of sensory information), and matching (i.e., user movement and system information match) (Slater et al., 1996). Immersion is an objective, "technology-related" aspect of virtual environments (Slater and Wilbur, 1997) whereas presence is a psychological, perceptual, and "feel of being there" (Slater et al., 1996). Immersion is an important feature of VR research because it influences a user's experience in VR and affect the user's sense of presence. There exists different VR technologies that can be group into three general categories – non-immersive, semi-immersive, or fully immersive. Table 1 lists the immersion categories and a few examples of the technology associated (Mujber et al., 2004). Several researchers have constructed frameworks and questionnaires to assess immersion and presence (Constantin and Grigorovici, 2003; Insko, 2003; Slater and Wilbur, 1997; van Baren and IJsselsteijn, 2008; Waterworth and Waterworth, 2001; Witmer and Singer, 1998). The potential for a specific user to become immersed in VR has even been shown to be subject to a person's personality traits (Samana et al., 2009). While physiological factors such as heart rate and skin conductance have been studied for correlation to immersion (Meehan et al., 2002) but these methods are used less often than questionnaires. Though immersion has been discussed in other domains like gaming (Ho, 2016), it has been largely discounted within the field of rehabilitation. Possible associations between immersion and user performance could be discovered with significant outcomes.

Some risks associated with immersion in a VE have been identified, such as simulator sickness. Extended participation can often lead to undesired physical symptoms such as eye strain, dizziness, and ataxia (Kolasinski, 1995). Therefore, it is important to account for these tendencies in experimental design and record any accounts of simulator sickness in the report.

One factor that has been shown to have an effect on immersion is the inclusion of haptic feedback within the environment and it has garnered much attention (Deutsch et al., 2008; Stone, 2001). Haptic response simulates kinesthetic information such as force and pressure through various hardware devices seeking a more real environment. Visual stimuli are present in VR but a lack of haptic feedback throughout an interaction with the environment impedes humans from rousing one of our five central senses (Akay, 1998). Haptic feedback has been shown to increase the sensory fidelity of VR; with the addition of more senses stimuli into the VR experience or through refining a particular sensory channel can help a user decide to continuously attend to VR (Chertoff et al., 2010). The presence of haptic feedback has importance to VR applications because it provides another form of communication to users.

To expand the degree of interactivity, task enjoyment can be altered to improve the engagement of the patients. Burke et al. (2009) presented gaming principles for stroke patients that were shown to increase engagement through motivating tasks. Further studies expressed the increased levels of enjoyment while performing PT exercises within the VE (Ho, 2016; Jack et al., 2001). Virtual reality in the field of healthcare research has been shown to be useful and effective because of its customization, interactivity, and ability to influence commitment through engaging tasks. There appears to be various features of VR that can be exploited for healthcare application.

2. Review objectives

We have identified three key aspects, in the form of research questions, in virtual reality and their attractiveness for rehabilitation. This review aims to understand three aspects of VR in rehabilitation – immersion, enjoyment, and haptic feedback – and any influence they may have on the performance and outcomes of patients. This review will shed some light on the capabilities of VR in rehabilitation and its impact on intervention outcomes, as well as identify gaps in the VR rehabilitation domain. Three research questions (RQs) are as following:

Research Question (RQ) 1 – How does the level of VR immersion affect user performance and/or health outcome?

Immersion in VR has been studied across many domains, but its correlation to rehabilitation and health interventions has not been explicitly considered. Examining immersion and identifying potential relationship between immersion and patient performance and outcome could be of value to future researchers.

Research Question (RQ) 2 – What facets of VR enjoyment have been researched relative to improved patient adherence?

The aspect of interactivity and enjoyment associated with VR has been well established. The prospective benefit it provides to patient adherence (to rehabilitation plans) has not be fully explored.

Research Question (RQ) 3 – What influences do haptic feedback on individual performance in VR?

Researchers are currently testing different haptic feedback varieties during VR rehabilitation studies. Early studies show benefits of incorporating haptic feedback in VR-based rehabilitation studies (Boian et al., 2003). The utility of haptic feedback in VR has not been thoroughly examined and the findings for this RQ can inform the design of future VR rehabilitation devices.

3. Review method

We systematically searched for literature regarding patient performance and health outcomes and experience of VR-based rehabilitation to address the following RQs:

1. How does the level of VR immersion affect user performance and/or health outcome?
2. What facets of VR enjoyment have been researched relative to improved patient adherence?
3. What influences do haptic feedback on individual performance in VR?

3.1. Eligibility criteria

To be included in this review, the VR device and methods used had to be explicitly stated. The studies also had to be within the physical rehabilitation domain.

3.2. Information sources

The following online databases were searched to yield a broad spectrum of results:

- **Web of Science** was used to provide an all-encompassing scientific search.
- **Compendex** was used for a primarily engineering centered search.
- **IEEExplore** was used to provide an electronic based search.
- **PubMed** was used for a healthcare-oriented search.

The literature search was limited to year 2005 in considering how rapidly VR technology progresses. The total literature search period lasted approximately eight weeks with the final search being conducted in October 2016.

3.3. Search

The general search strategy included key terms such as “virtual reality” and “rehabilitation”. A more focused approach to search was needed for each of the three research questions. Terms such as “immersion” for RQ 1, “enjoyment” and “adherence” for RQ2, and “sensory” and “feedback” for RQ3. Boolean search logic (e.g., “rehab*” instead of “rehabilitation”) allowed us to discover a wider range of relevant studies.

3.4. Study selection

Originally, “physical therapy,” “clinical patients,” “chronic pain,” and “immersive VR technology” were included in the search and no yielded results in the databases used. It was then extended to a combination of clinical and healthy individuals, rehabilitation, and both immersive and non-immersive VR devices. Each of these variables is stated in the tables and discussed in the results.

For RQ1, studies had to include measures of immersion and rehabilitation outcomes. For RQ2, VR enjoyment and adherence to plan were necessary discussion topics in order to be included. Adherence criteria included adherence to actual baseline follow-up studies and willingness to adhere to home-based VR rehabilitation. For RQ3, haptic feedback was the main search criterion. Also important was a study design that used the presence of haptic feedback as an independent variable.

The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) method was used to assist the accuracy and reliability of reporting of this review (Liberati, 2009). The PRISMA method employs a 27-item checklist and a four-phase flow diagram to improve the methodology of developing a systematic review or meta-analyses (Fig. 1).

3.5. Data items

Information was extracted from each included article to focus on the following variables:

- Population: A large (n > 20), mixed population (clinical and healthy) was ideal but due to limited studies in this domain, the search was expanded to smaller and occasionally asymptomatic populations.
- Outcomes: Studies needed to present comparative tangible results. For RQ1, measure of immersion was required. For RQ2, reported enjoyment through self-report or standardized questionnaire was required. A positive relationship was pursued for each RQ. For RQ1, the relationship was between immersion and participant performance. For RQ2, the relationship refers to enjoyment and patient adherence. For RQ3, the relationship between haptic feedback and user performance was examined.
- Study designs: The preferred study design would present two comparison conditions (different levels of immersion, with/without haptic feedback, etc.) and compared physical and behavioral results. Longitudinal studies were preferred for answering RQ2.

4. Review results

4.1. Study selection

Eighteen selected studies were included in this review. Initial searches from the specified databases with duplicates removed yielded 1061 results. It was further narrowed down to 99 using title and keyword searches. After each study was thoroughly reviewed, 18 articles

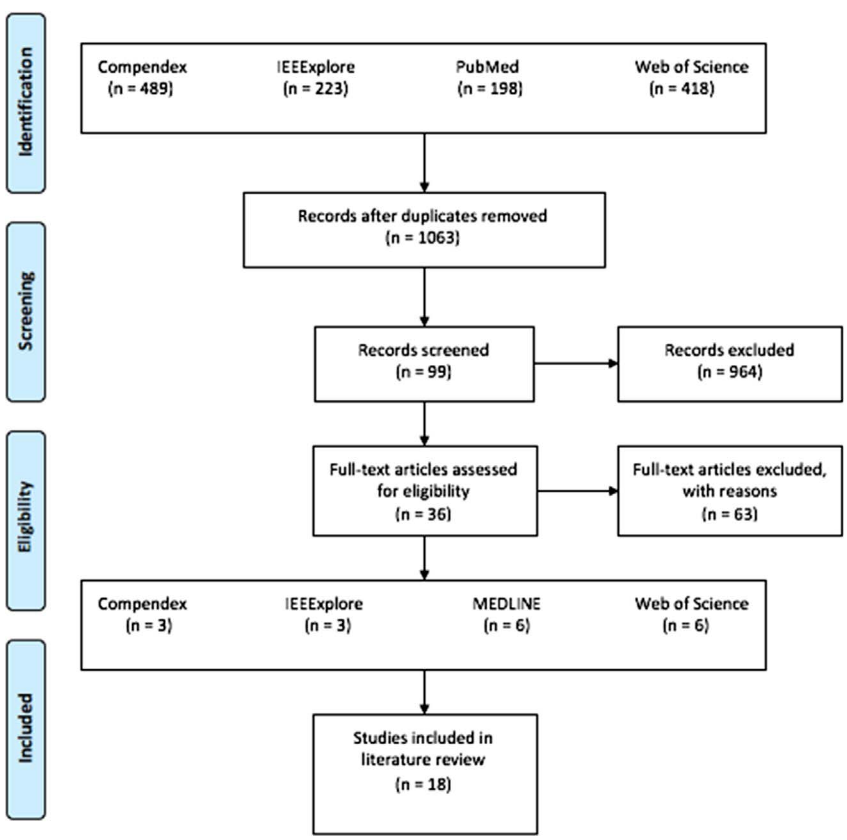

Fig. 1. PRISMA four-phase flow diagram.

Table 2
Studies selected for RQ1.

	Subramanian et al. (2008)	Lloréns et al. (2013)	Slobounov et al. (2015)	Bailenson et al. (2008)	Rand et al. (2008)	Crosbie et al. (2006)	Gokeler et al. (2014)
Objective	To compare shoulder movement patterns when performed in a head-mounted display (HMD) or screen projection system	To study mobility variables of a VR-based balance rehabilitation system for patients with acquired brain injury	To examine the effect of immersive 3D presentations and less immersive VR environments	To study the effect of interactivity on learning physical actions in VR	To investigate the potential of using a low-cost video-capture VR platform for rehabilitation	To assess the interaction of the user in terms of immersion in the VE and their perceived exertion	To evaluate the influence of immersion in a VE on knee biomechanics
Number of participants	9	10	27	65	56	17	40
Participant characteristic	Stroke	Stroke	Asymptomatic	Asymptomatic	Stroke	Stroke	ACL injury
Display type	HMD	Panoramic TV	3D Glasses	CAVE	Video-capture (screen)	HMD	Projection system
VR Model	Kaiser XL50	N/A	CrystalEyes stereo glasses	N/A	PS EyeToy	N/A	N/A
Immersion determinant	Questionnaire	Questionnaire	Questionnaire	Questionnaire	Questionnaire & Comparative	Questionnaire	None
Immersion Q	Witmer & Singer	Modified Witmer & Singer	0-10 Scale	Basic Likert Scale	Witmer & Singer, Slater	Witmer & Singer	N/A
Immersive tier	Fully	Semi	Semi	Semi	Semi	Fully	Semi
Upper or lower limb	Upper	N/A	N/A	N/A	Upper	Upper	Lower
Inclusion/exclusion	Shoulder pain, brainstem/ cerebellar stroke, or other neurological conditions affecting arm/trunk excluded	Unilateral neglect syndrome, ataxia, comprehension deficits, and severe visual problems excluded	History of neurological disorders, ADD, or injuries affecting balance excluded	None	None	None	Grade three injury of collateral ligaments, swelling or varus malalignment of knee
Positive relationship?	No	Yes	Yes & No	No	Yes	Yes	Yes

Table 3
Studies selected for RQ2.

	Parry et al. (2015)	Bryanton et al. (2006)	Rand et al. (2008)	Thornton et al. (2005)	Subramanian et al. (2007)	Sharar et al. (2007)
Objective	To compare compliance in patients receiving two types of rehabilitation systems	To compare virtual reality with conventional exercises in terms of enjoyment and compliance	To investigate the potential of using a low-cost video-capture VR platform for rehabilitation	To explore benefits of exercise participation perceived by participants and their caregivers	To confirm the effectiveness of training in a VE compared to PE regarding enjoyment	To assess the efficacy of IVR patient factors associated analgesia
Number of participants	17	16	56	27	12	146
Participant characteristic	Severe burn	Cerebral palsy	Stroke	Traumatic brain injury	Stroke	Severe burn
Display type	Video-capture	Computer	Video-capture (screen)	Computer	HMD/CAVE	HMD
VR model	PS EyeToy	N/A	PS EyeToy	N/A	Kaiser XL 50	nVisor SX
Length of study	6 months	90 min	40 min	3 months	2 Weeks	7 days
Interventions	Baseline, 3 weeks, 3 months, 6 months	N/A	N/A	Baseline, three times per week for 6 weeks, 3 month follow-up	5 days per week	Unknown
Dropout rate	6 dropouts	N/A	N/A	Unknown	Unknown	Unknown
Upper or lower limb	Upper	Lower	Upper	N/A	Upper	N/A
Inclusion/exclusion	Preexisting neurological deficits, upper limb amputations, inability to abstain follow-up excluded	None	None	Vestibular, vertigo, or orthopedic problems that severely limited mobility excluded	Shoulder pain, brainstem or cerebellum stroke, or orthopedic conditions affecting arm/trunk excluded	None
Positive relationship?	No	Yes	Yes	Yes	Yes	Yes

were eventually selected by relevancy to the specific RQs. One study was reviewed for RQ1 and RQ2.

4.2. Results of individual studies

4.2.1. Studies selected for RQ1

The objective of RQ1 is to understand the effect of immersion on human performance during rehabilitation in VR, and therefore only studies that compared at least two types of VR technologies that had different levels of immersion were used. To allow for comparisons across research studies, only those that quantitatively measured immersion and/or presence were included (Table 3). Studies that compared a VR group to a physical environment group were excluded.

Studies that investigated the effect of immersion in fully immersive devices indicated conflicting performance results. Subramanian et al. (2008) investigated the upper extremity movement patterns of patients who received visual display from a head-mounted display (HMD) and a rear-projection system. Both healthy individuals and stroke patients were assessed in shoulder flexion, elbow extension, and shoulder horizontal adduction range of motions (ROM), among others. Presence in the environment was evaluated with the Witmer & Singer Presence Questionnaire (Witmer and Singer, 1998). Although HMD was the more immersive device, results indicated no statistical difference in ROM between the two media. Bailenson et al. (2008) compared different physical training exercises between participants in an immersive CAVE to those using a 2D video screen. Although the observed outcomes did not indicate improved performance, participants in the immersive medium reported that they learned better, enjoyed the experience more, and thought that the virtual teacher was more credible than in video. Crosbie et al. (2006) studied the effect of immersion on reach and retrieval movements for virtual objects in stroke patients. They concluded that there is a positive relationship between immersive tendency and movements.

Inconsistent relationships between immersion and performance were also seen in studies using non-immersive or semi-immersive devices. Lloréns et al. (2013) examined the effectiveness and satisfaction of a VR based balance rehabilitation system for stroke patients in a longitudinal training program. Using a semi-immersive interactive panoramic screen with tracking capabilities, the patients subjectively felt “being present” during the virtual experience (4.1 rating out of 5, 5 being most present). During the weekly hour-long sessions, both of their physical performance and self-reported performance improved when the sessions took place in the training program. Patients even showed increasing progression after a one month follow up. Gokeler et al. (2014) studied the influence of immersive VR rehabilitation on knee movement patterns, kinematics, and kinetics of patients after anterior cruciate ligament reconstruction. Not only did patients experience improved knee movement when immersed in the projection-based VR, the focus of attention to the task was also increased positively associated with immersion. Involving strictly asymptomatic population, Slobounov et al. (2015) examined differences in postural stability and navigation success rates between 3D VR and 2D projection screen in spatial navigation tasks. Electroencephalography revealed that participants in the 3D VR condition allocated more sensory resources for cognitive and motor control during both postural stability and spatial navigation tasks. The subjective “sense of presence” and performance in terms of spatial navigation success rates were statistically significantly higher in 3D VR. Rand et al. (2008) studied enjoyment, immersion, and perceived exertion of stroke patients in low-cost video-capture VR platforms (Playstation II EyeToy and Gesturetek IREX). Patient subjective responses from the Witmer & Singer Presence Questionnaire indicated no statistical difference in presence between EyeToy and IREX. However, using the presence questionnaire by Slater and Wilbur (1997) indicated that EyeToy was more immersive than IREX. The perceived exertion was significantly higher when using EyeToy as indicated by Borg's Scale of Perceived Exertion (Borg, 1990), suggesting that users expended more effort when using the device during rehabilitation.

4.2.2. Studies selected for RQ2

Adherence to rehabilitation plans is of great importance for successful recovery. Research question 2 aims to examine the enjoyment aspect of VR rehabilitation on patient adherence (Table 2). Studies employing longitudinal studies were preferred for inclusion but exceptions were made if clear and distinct adherence conclusions were drawn.

Two studies indicated similar results regarding the relationship between enjoyment and performance in fully immersive VR. Subramanian et al. (2007) explored the effectiveness of upper limb mobility training in VR post-stroke. Stroke patients who received training in VR expressed greater engagement and motivation, and reported more enjoyment compared patients in the physical environment group. Sharar et al. (2007) assessed the recovery and subjective experience of burn patients as they underwent ROM physical therapy through standard care plus VR intervention or standard care alone. On a scale from 0 (least fun) to 100 (most fun), patients who received standard care plus VR intervention reported an average fun score of 73.7 ± 3.1, and those who only received standard care reported an average of 18.7 ± 3.1. The authors speculate that the entertainment value associated with VR during painful treatment can be a valuable incentive for patients to be more cooperative and consistent in their therapy.

Studies involving non-immersive or semi-immersive VR technologies had varying outcomes. Parry et al. (2015) randomly assigned pediatric burn patients to the semi-immersive VR group (PlayStation II EyeToy) or the standard therapy group, and they examined planar and functional ROM, adherence to intervention plan, pain, enjoyment, and exertion. After a six-month follow-up, results revealed an average of 90% days of adherence for the semi-immersive VR group compared with 85% in the standard therapy group. Due to limited data, this outcome was not statistically significant ($p = 0.43$) enough to be fully considered. Bryanton et al. (2006) studied the difference in enjoyment between VR and standard exercise programs for children with cerebral palsy. Enjoyment and adherence were assessed by a yes or no response to the following questions: “Did your child have fun?” and “Would your child exercise at home?” Both questions elicited significant increases in “yes” responses for the VR group, suggesting a positive relationship between the two elements. Rand et al. (2008) compared PlayStation II EyeToy against Gesturetek IREX in terms enjoyment, immersion, and perceived exertion. Patients revealed greater enjoyment level when using EyeToy compared to IREX, which may better encourage patients to perform prolonged upper extremity movements during rehabilitation. Thornton et al. (2005) studied the perceived benefits of exercise participation in VR by adults with traumatic brain injury. However, this study focus primarily on caregiver testimonials. The results suggested that patients who received VR expressed greater enjoyment and had better adherence to the intervention regimen, and they showed higher activities-specific balance confidence compared to the standard care group during the 3-month follow-up program.

4.2.3. Studies selected for RQ3

Providing multiple modes of feedback enhances the vividness and immersion of VR experience, which may potentially influence on user performance. Research question 3 focuses on the influence of haptic feedback technology on human performance in non-immersive and fully immersive VR technologies (Table 4). Haptic feedback, or any haptic-related sensory information displayed by the VR technology is included.

Three studies investigated the effects of haptic feedback on body kinematics in fully immersive VR. Ebrahimi et al. (2016) employed a combination of stretches and interactive games to characterize certain properties of human reach motion, in the presence or absence of haptic

Table 4
Studies selected for RQ3.

	Ebrahimi et al. (2016)	Magdalon et al. (2011)	Deutsch et al. (2008)	Ramírez-Fernández et al. (2015)	Levin et al. (2015)	Cameirão et al. (2012)
Objective	To characterize the human reach motion in the presence of visuo-haptic feedback	To compare kinematics of reaching and grasping movements performed in an immersive VE with haptic feedback	To test the contributions of visual stimuli and haptic effects to users gait on a walking simulator	To exhibit that haptic feedback in upper limb motor therapy improves performance and generates a lower mental workload	To characterize reaching and grasping parameters with and without haptic feedback	To compare the impact of VR-based training with three different types of interface systems
Number of participants	63	10	11	30	12	44
Participant characteristic	Asymptomatic	Asymptomatic	Asymptomatic	Hand motor impairments	Stroke	Stroke
Display type	HMD	HMD	Projector	Computer	HMD	Computer
VR model	nVisor SX111	Kaiser XL50	N/A	N/A	Kaiser XL 50	N/A
Haptic device	Stylus	Cyberglove	Rutgers Mega-Ankle	Novint Falcon	Cyberglove	Force-feedback handles
Upper or lower limb	Upper	Upper	Lower	Upper	Upper	Upper
Inclusion/exclusion	None	Visual or perceptual problems, movement impairments that would interfere with reaching/grasping excluded	Weighing over 150 lbs and taller than 5′7″, musculoskeletal pathology excluded	None	Hemispatial neglect, visual field deficits, apraxia, shoulder pain, other neurological conditions excluded	Severe to moderate aphasia and other cognitive and visual deficits excluded
Positive relationship?	Yes	No	No	Yes	No	Yes

feedback while wearing an HMD. The performance variables studied were reach accuracy, time to complete reach, distance traveled, and average reach velocity. Results showed that asymptomatic participants in the haptic feedback condition were more accurate on estimating distance to target and judging depth as compared to the no haptic feedback condition. Magdalon et al. (2007) examined the kinematics of reaching and grasping movements of three objects (can, screwdriver, and pen) in asymptomatic participants in fully immersive HMD with and without haptic gloves. Kinematics including elbow extension, shoulder flexion, and shoulder adduction were assessed with and without haptic gloves. Movements were found to be slower and grip apertures wider when wearing the glove during a reach-to-grasp task. Levin et al. (2015) characterized the reaching and grasping kinematics of three objects with and without haptic feedback in post-stroke patients in fully immersive HMD with a haptic glove. Using their hemiparetic arm, patients reached and grasped objects that required cylindrical and power grips, and precision pinch. Results indicated that time to complete reach was longer with haptic feedback, while arm trajectory, joint range of motion, and grasping kinematics were not statistically significantly different between the haptic feedback and no haptic feedback conditions.

Three studies examined human performance in non-immersive VR and with haptic feedback. Deutsch et al. (2008) investigated the effect of haptic feedback on walking velocity and temporal spatial parameters of gait of asymptomatic participants in different simulated ground surface conditions. Participants walked in greater velocity during situations involving only visual feedback of simulated mud and ice, and they walked slower when there was haptic feedback of mud and ice. While kinematics of gait were modulated by haptic effects (shorter step length on virtual ice and increased forces during initial swing for simulated mud), participants subjectively reported that haptic feedback did not enhance realism. Ramírez-Fernández et al. (2015) deployed a non-immersive computer setup to explore the effect of haptic feedback in upper extremity motor therapy, specifically examined its effect on performance improvement and mental workload. Patients were instructed to complete virtual mazes using either a low-cost haptic device or a non-robotic gesture-sensing device. No difference in precision or efficiency was found during the addition and subtraction of the haptic device. Mental workload, however, was lower during study task when using the haptic device. Patients also believed that the haptic device would lead to more effective therapy results. Also using a non-immersive computer setup, Cameirão et al. (2012) compared across three feedback modes, where were vison-based, haptic feedback-based, and passive exoskeleton interface systems. The haptic-based system showed improvements in the "Box and Block Test" for manual dexterity compared to the other systems. Follow-up at 16 weeks further revealed that patients who received haptic feedback showed continued motor ability improvements in various upper extremity outcome measures, including Barthel Index, Fugl-Meyer arm, and Fugl-Meyer wrist/hand inventories. The vision-based and the passive exoskeleton systems did not demonstrate sustained improvements in the outcome measures.

5. Discussion

5.1. Summary of evidence

5.1.1. Evidence for RQ1

There were mixed findings on the effect of level of immersion in VR on user performance and/or health outcomes. Of the seven studies reviewed for this RQ, four exhibited a positive relationship between increased immersion and performance (Crosbie et al., 2006; Gokeler et al., 2014; Lloréns et al., 2013; Rand et al., 2008), two demonstrated no statistically significant relationship (Bailenson et al., 2008; Subramanian et al., 2008), and one had a combination of positive and negative results (Slobounov et al., 2015).

Subjective questionnaire results from Bailenson et al. (2008)

showed that the more immersive system, CAVE, was reported to have increased levels of enjoyment and improved learning aptitude, but the measured performance did not indicate superior outcome in the CAVE compared to the 2D video screen. This suggests that having self-report outcome measure alone or performance measures alone may not be sufficient (Bailenson et al., 2004, 2005; Slater, 2004); having both self-reported questionnaires and objective performance measures may provide greater insight on user subjective perception and actual outcomes. Incorporating physical measurements as outcome measures permitted an objective evaluation mental workload and postural stability in VR operation (Slobounov et al., 2015). More explanatory ability was demonstrated by studies with quantifiable measures: 3D immersion may be associated with greater posture instability during periods of movement, which was related to how human sensory system interpreted the visual information presented in the different environments. However, the success rate of the navigation task performance was significantly higher during the 3D than the 2D condition. This increased user performance with added immersion provides a positive response to the research question, supported with objective cognitive findings.

Reviewed studies did not directly quantify and compare immersion levels across different VR technologies, but rather assessed the relationship between subjective sense of presence (that is related to immersion) and objective user performance (Crosbie et al., 2006; Gokeler et al., 2014). It may not provide outside researchers with data directly related to immersion in VR. During the study conducted by Rand et al. (2008), sense of presence between EyeToy and IREX was too close to distinguish using the Witmer & Singer questionnaire, yet the Slater questionnaire established the EyeToy System as the more immersive of the two. This highlights the necessity of having a standardized and commonly accepted questionnaire to reveal subtleties in immersion levels of VR technologies. In addition, tasks performed with EyeToy was perceived to have greater exertion, which may be a characteristic to consider to conduct studies involving exertion tasks.

Overall, no consensus was found for a positive or negative relationship between immersion and user performance since study designs and outcome measures varied among studies. Rather, different aspect yielded different results. Postural instability was found to increase as immersion increased. Navigation task performance and assignment accuracy on the other hand was shown to improve with increased immersion. Joint mobility had mixed results, suggesting that more research needs to be done in the area.

Recommendations for future consideration. Subjective questionnaires were the primary method used for measuring immersion within a virtual environment on all seven studies for RQ1. Applying the similar questionnaire for assessment in different studies allows researchers to compare across studies. However, having objective measures along with subjective questionnaires may provide more explanatory data. For instance, monitoring brain activity may provide an alternative approach to objectively quantify performance (Slobounov et al., 2015), and many others have demonstrated its use in monitoring activities during motor function (Adkin et al., 2006). If questionnaires remain as a popular tool of measurement, then standardized questionnaires should be implemented for enhanced comparison purposes. In addition, as immersive VR technologies (e.g., HMD) start to become more economically feasible, such tools may gain greater popularity and evaluations of commercially available immersive VR technologies would be needed.

5.1.2. Evidence for RQ2

The objective of RQ2 was to examine what facets of VR enjoyment have been researched relative to improved patient adherence. Through gaming principles and interactivity, five of the six articles reviewed indicated that the enjoyment of VR in the domain of rehabilitation increased patient adherence to rehabilitation plans or willingness to stay engaged (Bryanton et al., 2006; Rand et al., 2008; Sharar et al., 2007; Subramanian et al., 2007; Thornton et al., 2005). Only one study quantified adherence (Parry et al., 2015). The remainder of the articles drew conclusions based on behavioral evidence and user testimonials (Bryanton et al., 2006; Rand et al., 2008; Sharar et al., 2007; Subramanian et al., 2007; Thornton et al., 2005).

Two studies employed cross-sectional experiments to examine participant response to determine adherence via questionnaires (Bryanton et al., 2006; Rand et al., 2008). Authors collected self-reported responses to suggest the likelihood of adherence and continued usage of VR rehabilitation equipment, but the actual long-term outcomes cannot be assessed. These responses may still be encouraging as they imply patient acceptance to VR technologies in healthcare.

The remainder of the studies were longitudinal, observing the adherence and outcomes patients over an extended period of time (Parry et al., 2015; Sharar et al., 2007; Subramanian et al., 2007; Thornton et al., 2005). Thornton et al. (2005) used a combination of participant testimonials and subjective measures to suggest both entertainment levels and potential for adherence. Psychosocial characteristics such as enjoyment, confidence, and self-esteem were evaluated from a caregiver's perspective with reassuring attitudes towards adherence. Statements from participants such as “looking forward to going” and “I just feel more confident” demonstrate the added enjoyment benefit of VR compared to standard PT. The work from Sharar et al. (2007) and Subramanian et al. (2007) indicated similar results. On the other hand, Parry et al. (2015) studied burn patients over a 6-month span and no statistical significant difference was found between the VR group and standard therapy group in their ratings of enjoyment. A small difference was observed in number of days of adherence occurred between the VR group (90%) and standard therapy group (85%), but there were six study dropouts (initially $n = 17$, final $n = 11$) and it was difficult to suggest true adherence capacity.

Recommendations for future consideration. The common theme among researchers is that enjoyment in VR provides patients with an increase in rehabilitation plan acceptance and willingness to participate - largely due to interactivity and game-based training systems. Testimonial and behavioral results may provide insights on patient opinions regarding the VR experience and the tendency to adhere to the care plan. Studies should implicitly measure adherence over a study period to reveal a more representative adherence capacity. One major challenge with adherence studies is the likelihood of patient dropouts since the experiment is stretched out over a longer period of time (Wolke et al., 2009) and it was observed in one of our reviewed studies (Parry et al., 2015). Small sample size may not have had enough statistical power to indicate an effect of VR enjoyment on patient adherence, it is suggested that having at least 20 participants would allow for significant results while still providing leeway in case of a notable dropout rate (Abdullah et al., 2015).

5.1.3. Evidence for RQ3

Research question 3 was “What influences does haptic feedback on individual performance in VR?” The effect of haptic feedback on upper and lower extremity kinematics and performance were examined. Three out of the six studies demonstrated a positive relationship between the presence of haptic feedback and improved task performance (Cameirão et al., 2012; Ebrahimi et al., 2016; Ramírez-Fernández et al., 2015). Movement speed was affected by haptic feedback in VR.

Two studies utilized a haptic glove for providing haptic feedback (Levin et al., 2015; Magdalon et al., 2011). Similar results between the two studies showed that grip apertures were wider when there was haptic feedback from a haptic glove. Reaching movements were slower when wearing the glove, while joint ranges and various grasping parameters were unaffected. This does not necessarily mean that the glove will produce subpar rehabilitation results, but instead may speak more to the individuals’ familiarity to movements in VR (Magdalon et al., 2011). Further training with the unfamiliar technology could improve future findings.

Other upper extremity studies focused primarily on movement accuracy, precision, efficiency, and strength as a few of the dependent variables. Involving asymptomatic individuals in VR, Ebrahimi et al. (2016) found movement accuracy, depth judgement, and hand path efficiency were better when there was haptic feedback from a stylus than without haptic feedback. Cameirão et al. (2012) found comparable results. Along those same lines, Ramirez-Fernandez and colleagues (2015) also indicated higher precision of movement using the haptic device and lower mental workload during the task. The common theme among grasping tasks was a decrease in movement velocity using a haptic glove. A decrease in movement velocity during rehabilitation procedures could show that the use of haptic gloves may not provide the patient with comfort and/or confidence in the system.

Deutsch et al. (2008) used two Rutgers Mega-Ankle robot platforms to simulate different haptic-influenced environmental walking conditions involving asymptomatic individuals and the results indicated that walking velocity decreased when there was haptic feedback. Providing different modes of feedback may be used to modify rehabilitation procedures, such as intended rehabilitation gait speed.

Recommendations for future consideration. Although this research questions dealt primarily with the effects of haptic feedback, a continuation onto effects of auditory feedback could also provide beneficial knowledge. Visual, tactile, and auditory are the three primary senses stimulated by current VR technology. Until future engineers can incorporate taste and smell into the VE, each of the three current senses should be researched until they are fully understood in relation to user performance.

5.2. Review limitations

This review was limited by the following factors:

- Limitation of studies that included immersion measures. Most VR rehabilitation research is proof-of-concept, which usually did not call for immersive quality discussion.
- Limitation of studies that include a combination of both enjoyment and adherence and the inclusion criteria were relaxed to cross-sectional and self-report adherence studies.
- Post-injury timeline data were not considered as inclusion criteria. Future reviews should consider this as a potential factor.
- Date of publication. Due to the rapid progression of technology, many older studies had to be excluded which severely limited the selection.
- Amount and variety of online databases searched.
- Article quality assessment. Future systematic literature reviews should consider using quality assessment tools such as the Physiotherapy Evidence Database (PEDro).
- Only studies in English were included.

6. Conclusions

We reviewed current literature on VR technologies from a user performance perspective focusing on three core issues. The effect of immersion on user performance/health outcomes, facets of enjoyment relative to user adherence, and influences does haptic feedback on individual performance in VR. Each of these concerns was evaluated on the basis of user performance in VR rehabilitation settings.

We found that no distinct correlation can be outlined between increased immersion and improved user performance/motor recovery. Increased immersion was shown to improve navigation task performance and assignment accuracy but also postural instability. Joint mobility had both positive and negative associations to immersion growths. In addition, no comprehensive agreement was found between enjoyment and user adherence. While one study found no significant evidence linking the two characteristics, each of the other articles advocated that there is indeed a positive relationship between them. Finally, different haptic devices influenced performance; using haptic glove was shown to decrease movement velocity while presence of haptic controllers increased movement accuracy and path efficiency. When lower extremities were presented with haptic feedback, velocity was effected based on the combination of visual and haptic stimuli.

The recommendations for future consideration proposed provide a general idea of what direction research in this domain should be heading. The potential of VR for rehabilitation is not fully explored. There is the need for longitudinal and follow-up randomized control trials on VR rehabilitation interventions.

Conflicts of interest

The authors have no conflicts of interest.

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