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EDITORIAL

Unlocking the potential of virtual reality for post-stroke sensorimotor rehabilitation - are we any closer?

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1. Introduction

Virtual reality (VR) technology has advanced considerably in recent years and the number of assistive devices available for physical rehabilitation has been steadily growing. VR technologies for rehabilitation are defined as 'any interaction (physical or cognitive) in real-time in an artificial environment generated by a computer or a mobile device that appears and feels similar to real-world objects and events' [1]. In a VR application for rehabilitation, movements of the body are usually tracked by a motion-tracking device and projected onto a computer or large screen so that the individual can interact with virtual objects. Despite the promised advantages of VR applications to enhance sensorimotor recovery after musculoskeletal and neurological injury or disease, there are some important drawbacks for its use as an adjunctive rehabilitation intervention.

VR technologies hold considerable promise to improve sensorimotor rehabilitation outcomes through the implementation of ecologically valid, intensive task-specific training, linked to better recovery [2]. VR has the added benefit of enhancing the engagement of the user, for instance by allowing for gamification that may increase motivation for training (e.g [3]). It furthermore promises to do so in a cost-effective way although this may vary depending on the application platform and method of delivery [4]. Indeed, while the cost benefit of the integration of VR in rehabilitation may be promising, few studies have specifically addressed this question [4]. Several reviews have suggested that VR as an adjunct treatment modality, specifically in stroke rehabilitation, has already partially met some of these promises [5].

Due to the promise of VR, there has been a growing number of virtual assistive devices developed worldwide, incorporating innovative technological advances for physical rehabilitation of mobility and/or movement disorders due to aging or disease. These include platforms such as telerehabilitation (i.e. exercise interventions delivered remotely from the clinical environment via telecommunication technology), augmented reality (i.e. the superposition of virtual digital images onto the physical environment, such as virtual obstacles to step over which are projected onto the physical floor) and mixed reality that can include both virtual and physical objects projected either in a virtual or physical environment. The advantage of VR is that it allows activities to be created that address a wide variety of sensorimotor disorders, permits practice of activities in a safe and controlled environment, can provide flexible reward and error feedback to enhance motor learning and offers a motivating and rewarding environment to encourage learner engagement and interest. Accumulating evidence suggests that virtual rehabilitation provides additional possibilities both in and out of clinical settings via telerehabilitation for individuals to improve sensorimotor recovery after central nervous system injury or disease by offering more opportunities for intensive task-specific practice.

However, there are some downsides to the use of VR. Aside from technical and economic constraints that limit the uptake of VR into clinical practice [6], there are additional psycho-neurophysiological considerations. VR replaces natural sensory inputs that guide movement with computer-generated signals. This alters the perceptual environment, since virtual signals may be missing or may be different from natural ones, and therefore may introduce uncertainty about object location or orientation [7]. These perceptual alterations include unnatural or conflicting depth cues (e.g. vergence-accommodation conflict [8]), limited field of view, missing or inaccurate haptic information, distortions of space, and small rendering lags due to the artificial presentation of egocentric distance cues in virtual environments. Are such erroneous and/or conflicting signals a problem? One might argue that putting on prescription glasses also leads to some erroneous visual cues. Why would the erroneous cues be more problematic in VR than in the real world?

The reason that erroneous or conflicting visual cues are not a problem in real life is that in the physical world, we receive haptic information when interacting with the environment, particularly for tasks involving object manipulation. This information can be used to deal with conflicts between visual cues [9]. Haptic spatial information is related to the tactile inputs from the periphery and efferent signals from the cortex based on a distributed neural network [10]. Haptic perception of object shape from the relative positions of cutaneous mechanoreceptors in the hand critically guides the ability to interact with objects and requires the integration of cutaneous and

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proprioceptive signals. This means that the presence of haptic information is essential for normal performance. For instance, in grasping, consistent haptic feedback is required for natural scaling of movement parameters to object properties [11,12], as illustrated by the lack of normal grasping behavior of a patient with object agnosia without haptic feedback [13]. Individuals with lesions affecting the integration of sensory information struggle to perform even the most basic activities of daily living, like picking up a cup or using a toothbrush [14]. Indeed, the congruency between sensory information and action plays an important role in neuroplasticity and the restoration of motor functions [15].

Most current VR systems do not yet accurately incorporate realistic haptic information of the interaction of the body with the environment. This is particularly important for improving function of the upper limb, but may be less relevant to whole-body action such as retraining trunk stability and locomotion. Diminished haptic information leads to differences in reach-to-grasp kinematics in VR compared to physical environments. In line with our previous arguments, reaching movements in a haptic-free VR environment differ from normal movements. They are slower, have longer deceleration times and hand aperture timing and amplitudes are altered [16]. These differences persist but are less evident even when some haptic information is provided [17]. The persistence of alterations in reach-to-grasp movement kinematics in VR means that while VR technologies offer innovative opportunities for learning motor skills in more flexible ways, a significant gap still exists in our understanding of how skills performed in VR differ from those in the real world and how this affects the rehabilitation goal of reducing upper limb motor impairment.

Another downside of the use of VR is what happens after exposure, as there are reports of reduced postural stability after the use of VR. This decrease in stability is presumably due to reduced reliance on visual information for postural control after VR exposure [18]. Reduced stability might lead to falls, which would interfere with the rehabilitation process. It is unclear to what extent this is due to the sensory conflicts that we have discussed above, or due to the large-scale visual motion that is present in VR games and flight simulators, but to a lessor extent in VR rehabilitation applications.

Traditional training approaches are based on the notion that motor behavior can be improved simply by repetitive practice of the same or multiple movements [2,19]. However, the 'more is better' approach fails to account for the fact that repetitive practice of the 'wrong movements' leads to 'bad neuroplasticity.' There are several reasons why movements might be incorrect when training using VR. One reason is that the initial response to a deficit may be the use of undesirable (i.e. compensatory) movement patterns [20]. Another reason is that the training in VR itself will induce undesirable movements, for instance due to the altered visual environment and the lack of haptic feedback. Thus, since the natural response to disability is to learn new ways of accomplishing daily activities, i.e. to develop compensatory behaviors, without proper physiological cues, repetitive practice may likely only reinforce the wrong movements [21]. Reinforcement of these movements in VR may thus interfere with true motor recovery of natural movement patterns [22].

Indeed, while most physical training interventions are based on established principles of motor learning and neural plasticity [23], recovery potential depends on remediating an individual's specific motor impairment – an approach called *impairment-oriented training* [24]. In this approach, the focus is on diminishing motor impairment i.e. recovering the ability to produce active movement in specific joint ranges by repairing the underlying motor control deficit [25]. Impairment-oriented training depends on the ability of the learner to recognize and adapt specific joint coordination during the performance of a task. This is true of training in both a physical and a virtual environment and is accomplished through proprioceptive and tactile feedback during movement.

2. Conclusion

Despite the promise of VR to augment sensorimotor rehabilitation outcomes, the present technology does not completely reproduce the perceptual and haptic qualities of the real world that are necessary for meaningful interactions with the environment. Thus, when the goal of the rehabilitation intervention is to diminish sensorimotor impairment, we should exercise caution when implementing VR for sensorimotor recovery until all relevant visual and haptic information can be adequately provided by the technology. However, when the goal is to increase general mobility through non goal-directed exercise, VR may be an effective intervention.

3. Expert opinion

Virtual reality technology has developed as a promising adjunctive therapy for rehabilitation and has been shown to increase the ability to deliver more intensive and meaningful training for people with mobility and sensorimotor disorders. Some benefits include greater motivation to engage in practice, improved clinical outcomes and greater use of the impaired limb or limbs. However, a drawback of current virtual reality technology is that it does not completely reproduce the perceptual and haptic requirements for meaningful interactions present in the natural environment, especially for upper limb goal-directed actions. Thus, retraining in such virtual environments may lead to learning non-desirable movement patterns that may interfere with true motor recovery of normal motor actions. A greater understanding of the effects of sensorimotor retraining in an altered perceptual environment is needed before we can fully adopt current virtual reality technology as a primary training environment. Technology will advance, but we are unsure how close we are to the moment that all limitations we discussed above for reducing sensorimotor impairment will be remediated, particularly for individuals with different pathophysiologies. Future progress in technology development, as well as its accessibility and cost-effectiveness, should focus on improving the incorporation of pertinent visual and haptic information to derive the most meaningful benefits for ecologically-relevant sensorimotor recovery.

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