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# Enhancing Upper Limb Rehabilitation of Stroke Patients With Virtual Reality: A Mini Review

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Upper limb motor impairment following stroke is a common condition that impacts significantly the independence and quality of life of stroke survivors. In recent years, scholars have massively turned to virtual reality (VR) to develop more effective rehabilitation approaches. VR systems are promising tools that can help patients engage in intensive, repetitive and task-oriented practice using new technologies to promote neuroplasticity and recovery. Multiple studies have found significant improvements in upper limb function for patients using VR in therapy, but the heterogeneity of methods and tools employed make the assessment of VR efficacy difficult. Here we aimed to assess the potential of VR as a therapy tool for upper limb motor impairment and to provide initial assessment of what is the added value of using VR to both patients and clinicians. Our mini-review focuses the work published since the Cochrane review (2017) and suggests that VR may be particularly effective when used in combination to conventional rehabilitation approaches. We also highlight key features integrated in VR systems that appear to influence rehabilitation and can help maximizing therapy outcomes, if exploited properly. We conclude that although promising results have already been gathered, more focused research is needed to determine the optimal conditions to implement VR in clinical settings in order to enhance therapy and to better define and leverage the true potential of VR. The rapid pace of technological development and increasing research interest toward VR-based therapy will help providing extensive knowledge and lead to rapid advancements in the near future.

**Keywords: stroke, upper limb, rehabilitation, virtual reality therapy, naturalistic**



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## INTRODUCTION

Stroke is the second leading cause of death and the third most common cause of disability worldwide (Feigin et al., 2017). The interruption of blood supply to the brain occurring during stroke can cause several physical and cognitive impairments that may highly affect patients' participation in activities of daily living (ADL) and their quality of life. In particular, hemiplegia represents the most prevalent impairment for stroke patients, resulting in impaired arm and hand movements, with deficits in motor control and grip strength. Upper limb motor abilities often remain affected after a stroke and become a chronic condition. In stroke patients with complete initial hemiplegia, longitudinal observational studies showed a very low recovery rate for the upper-limb, and the absence of functional recovery when the impairment remains complete after a delay of 3 weeks (Wade and

Hewer, 1987). Recent modeling showed that the probability to recover upper-limb motricity remains extremely low after 12 weeks post-onset (van der Vliet et al., 2020). Upper limb function plays a major role when performing ADL as many activities require the coordinated use of both hands (Ekstrand et al., 2016), and is strongly associated with the quality of life of stroke survivors (Nichols-Larsen et al., 2005). Thus, rehabilitation of upper limbs represents a major need and challenge in stroke management and motor rehabilitation is recommended to be initiated early in order to enhance the recovery process (Duncan et al., 2005).

Given the urgent need for effective approaches, innovative tools are currently being investigated as new treatment methods. A number of new technologies have emerged in the recent years and are becoming more accessible to rehabilitation clinics. In particular, virtual reality (VR) is being regarded as a promising treatment tool, and presents characteristics that may be beneficial for therapists' intervention and for the functional recovery of stroke patients (Bohil et al., 2011; Massetti et al., 2018). VR can be defined as "the use of interactive simulations created with computer hardware and software to present users with opportunities to engage in environments that appear and feel similar to real world objects and events" (Weiss et al., 2004, Introduction section, para. 2). Users can interact with a virtual environment using controllers, joysticks or a computer mouse to manipulate virtual objects. They can also be represented by an avatar within the virtual environment, whose movements will match those of the users by means of motion capture technology (Bohil et al., 2011). More particularly, VR systems may help stroke survivors engage in a virtual environment with sensory stimulations in multiple forms such as visual, auditory or haptic that can simulate real-life situations and help the practice of goal-oriented tasks in environments similar to the real world (Klinger, 2008).

For these reasons, the exploration of VR usages for clinical applications is increasing rapidly, with an ever-growing number of publications in the past few years (Garrett et al., 2018). In stroke rehabilitation research, the use of VR is often compared with conventional therapy (CT) delivered by physical therapists and occupational therapists. The updated Cochrane review by Laver et al. concluded in 2017 that VR-based therapy was not more beneficial than CT for improving upper limb function. Specifically, they report that VR "may be beneficial in improving upper limb function and activities of daily living function when used as an adjunct to usual care (to increase overall therapy time)." (Laver et al., 2017, p. 2). Nowadays, VR is indeed used in clinical settings for rehabilitation purposes alongside CT and associated technologies have become more and more accessible and widespread.

These factors lead to frequent updates in rehabilitation research regarding the use of VR, its efficacy in motor recovery, and how it may be implemented in clinical settings. The aims of this mini-review are thus to 1) assess the current results regarding efficacy of VR therapy in upper limb rehabilitation following stroke and 2) start identifying potential characteristics of VR-based therapy that can be beneficial for upper limb rehabilitation for both clinicians and patients. As VR-based therapy is being extensively investigated, we aim to specifically provide a brief update on the growing state of research for upper limb rehabilitation, in order to inform on the recent developments on VR in rehabilitation but also to provide insights on how this field may progress in the future.

## Current Evidence Regarding the Efficacy of Virtual Reality-Based Therapy

Traditional methods for the rehabilitation of the upper limb in clinical centers are usually provided by physical and occupational therapists, including ADL training. Recent studies have reached the same conclusions as the Cochrane systematic review (Laver et al., 2017). Investigating a VR system specifically designed for upper limb rehabilitation and VR as a stand-alone therapy, Schuster-Amft et al. (2018) found that chronic stroke patients in both the experimental group and the control group improved their hand dexterity, arm function and independence in ADL after a 4-week treatment, with no between-group differences after the same amount of therapy. In line with the results of Laver et al.s' review, Hung et al. (2019) observed that a VR-based training combined with CT also did not lead to different results when compared with CT only, for the same amount of therapy and with similar training contents. Brunner et al. (2017) compared improvements in upper limb motor function after additional VR training with additional conventional rehabilitation, both provided as an adjunct to standard therapy, but did not observe significant differences between the two modalities, although they both led to significant improvement of all outcomes for subacute stroke patients, further suggesting that VR training is simply as effective as CT in upper limb rehabilitation.

However, several authors recently found conflicting results. Significantly greater improvements in upper limb motor recovery and gross manual dexterity were observed in several studies in either subacute or chronic stroke patients who benefited from VR training in addition to conventional treatments, as compared to patients who only had CT (Aşkın et al., 2018; Ikbali Afsar et al., 2018; Lee et al., 2018; Rogers et al., 2019). These improvements could at least in part result from the increased therapy time, as observed in Aşkın et al.'s study where patients in the experimental group had one more hour of therapy every day than the control group, but these studies may also suggest that VR-based therapy is an effective tool, especially when combined with CT. Importantly, Wang et al. (2017) and Kiper et al. (2018) compared stroke patients undergoing VR training along with CT with patients who had CT only, for the same amount of therapy in both groups. They observed a significantly greater improvement on motor function in the experimental group where VR training was added to canonical therapy. The recent work of Ain et al. (2021) also indicate improvements on upper extremity function in favor of the experimental group who underwent Xbox Kinect-based training and CT for the same duration.

The conflicting results observed in these recent studies could result from differences in their experimental protocols, which differ in number and frequency of the training sessions. We note that in studies where no difference was observed between VR and CT groups, patients received two to five rehabilitation sessions a week. In studies where a greater improvement was observed for VR groups, all patients received a more intensive therapy with sessions on 5 days a week. The various training frequencies thus resulted in different training time. For example, patients in Schuster-Amft et al.‘s study (2018) received a total of 12 h of VR-based training during 4 weeks, with no between-groups differences observed, while patients in Wang et al.‘s study (2017) received a total of 45 h of therapy during 4 weeks, with greater improvements for the VR group. These results may indicate a dose-effect relationship in VR therapy that needs further investigation to determine more precisely how many hours of VR per week are needed to make VR-based therapy effective in upper limb rehabilitation and how the dose impacts the outcomes.

Besides differing in intensity, different VR systems were also used in the studies, possibly concurring to explain part of the reported outcome differences. In addition to hand movement tracking, some of the systems presented distinct features, such as enhanced feedback and enriched virtual environment (Kiper et al., 2018; Rogers et al., 2019), the use of a sensorized real object (Kiper et al., 2018), hand-held objects (Rogers et al., 2019), the use of a controller (Lee et al., 2018), or an avatar hand of the patient’s movements appearing on the screen (Wang et al., 2017). Thus, groups of patients interacted differently with the virtual environments during their training depending on the system they used. Along with the development of VR technologies and features, we deem important that future studies will investigate if and what specific features of VR, such as augmented feedback, or the use of physical objects that patients grasp, may favour rehabilitation outcomes.

We additionally note that the studies included patients in the subacute phase, or in the chronic phase of stroke. Considering the delay since stroke, no stringent difference was noted between studies showing an additional beneficial effect of VR as compared to CT vs studies showing no additional effect of VR compared to CT. Interestingly four out of seven studies showing an additional effect of VR concerned patients in the sub-acute phase (Ikbali Afsar et al., 2018; Lee et al., 2018; Rogers et al., 2019; Wang et al., 2017), two studies concerned chronic patients (delay since stroke above 6 months) (Ain et al., 2021; Aşkın et al., 2018), and one concerned both subacute and chronic patients (Kiper et al., 2018). These results suggest that the likelihood to observe an additional gain provided by VR is increased at the sub-acute phase but a further improvement induced by VR therapy may also occur at the chronic phase.

Despite conflicting observations, these recent results contribute increasing evidence that VR therapy is not to be overlooked in upper limb rehabilitation as it may be concretely beneficial to patients’ recovery. The more consolidate findings so far suggest that VR could enhance CT and increase the rehabilitation potential. Rather than relying on one method, multiplying therapeutic approaches to include VR therapy in existing rehabilitation programs appears to be an effective way to further advance stroke rehabilitation outcome.

Effects of neuroplasticity as a direct result of VR therapy is also being investigated, but evidence is still modest (Laver et al., 2017). In their study on the combined use of VR and CT, compared with CT alone, Wang et al. (2017) evaluated the neural reorganization in sub-acute stroke patients with fMRI before and after training with a Leap-Motion based VR system. Patients were asked to perform movements where they had to use the thumb of their impaired hand to touch their opposite palm. They observed a shift in the sensorimotor cortex activation from ipsilateral to contralateral regions and an increased activation in the contralateral cortex in both the experimental and control group. Yet, this change was significantly greater in the experimental VR group. In addition, the experimental VR group also displayed larger improvement in the experimental group using the Wolf motor function test (WMFT), used to assess patients’ upper limb motor function. These findings suggest that repeated exercises with the affected limb and task-oriented practice in a virtual environment can facilitate neural reorganization to a larger extent compared to CT alone, promoting motor recovery of the affected upper limbs. Future neuroimaging studies will hopefully help better characterizing VR training dependent effects and thus guiding the development of VR as a therapy tool.

## Benefits of Integrating Virtual Reality as a Therapy Tool for Therapists

VR systems developed in the recent years display features that therapists can exploit for their expert intervention. The large number of studies conducted help provide more insights on which among those characteristics may come into play in VR-based rehabilitation, and how they may influence rehabilitation outcomes and/or the therapeutic protocols that can be conducted.

It has been widely documented that VR systems offer the ability to provide an intensive training with a high number of movement repetitions per session (Perez-Marcos et al., 2017). It is suggested repetition of movement and duration of training are factors that may optimize motor rehabilitation outcome and ability to perform ADL, although dose-response effects and difficulty level of each task should be assessed to ensure an optimal therapy dosing (Baniña et al., 2020; Dromerick et al., 2009; Kleim & Jones, 2008). VR systems are believed to help increasing the rehabilitation dosage and to provide significant amounts of therapy to patients thus enabling simulated practice of functional tasks (Laver et al., 2017). Perez-Marcos et al. (2017) and Baniña et al. (2020) reported that training with a VR-based motor rehabilitation system was indeed feasible and could provide high rehabilitation doses, with a high number of repetitions per session and active training time for more efficient training sessions. In Perez-Marcos et al.’s study (2017), various shoulder, arm and wrist exercises were proposed and integrated into functional tasks, like grasping or pointing at virtual objects, and led to significant improvements in upper limb function of chronic stroke patients.

It is also suggested that VR systems can help increase the dosage of therapy without needing to increase staffing levels (Laver et al., 2017). VR systems can be equipped with a tracking functionality, allowing therapists to monitor their patients' progression without the need for physical supervision at all time. Using the VR system and following an exercise program predefined by their therapist, patients can then participate in a more intensive and frequent training without increasing staffing and achieve positive results in their upper limb recovery (Norouzi-Gheidari et al., 2019). If successfully implemented, VR could then become a cost-effective rehabilitation tool.

In particular, these apparent benefits of VR technologies open new perspectives and opportunities for tele-rehabilitation, an emerging solution which allows patients to have access to a home-based therapy following discharge from the stroke and rehabilitation units and to extend patients' therapy duration, with remote monitoring from therapists (Allegue et al., 2020; Laver et al., 2020). Self-administered treatment at home, through technology-based training and conventional exercises, has been previously found to be accepted by chronic stroke patients (Nijenhuis et al., 2017). A few VR systems have been specifically designed for home-based use like the Neurofenix platform (Kilbride et al., 2018), aiming to encourage stroke patients to exercise independently at home, in their environment, and with minimal therapist supervision. Feasibility studies reported that patients, trained at their own home during 4 weeks, have gained significant improvements in bilateral upper limb function, grasp strength and motor control (Burdea et al., 2019; Thielbar et al., 2020). Findings from a recent study also suggest that VR-based training taking place at home can induce cortical reorganization and is associated with upper limb functional gains (Ballester et al., 2017). All these recent developments add to suggest VR is a technology of interest to spread the development of tele-rehabilitation for patients suffering from upper limb impairment and these positive results strongly encourage to conduct further studies on the use of VR at home, to determine the effectiveness of the intervention but also help guide therapists on how to effectively conduct their intervention remotely using these technologies. We argue that facilitating access to therapy in a remote location and an increased treatment period may turn out to be major arguments in favor of the use of VR in rehabilitation.

## Potential Ingredients That Render Virtual Reality-Based Therapy Effective

The above reviewed recent studies revealed several factors inherent to VR therapy that may highly enhance neurorehabilitation and participate in the significant improvement observed so far in upper limb function. We advance that it would be particularly interesting to accurately identify what those factors are, to help optimizing VR systems developed in the future for rehabilitation purposes.

It has been highlighted that the distinction between specialized or non-specialized VR systems might be an important factor in regards to efficacy (Aminov et al., 2018). Specialized systems are VR systems that were specifically developed for upper limb rehabilitation. Examples of specialized systems include SaeboVR, MindMotion Pro or Bi-Manu Trainer. Non-specialized systems refer to off-the-shelf systems and commercial gaming systems, such as the Nintendo Wii or Microsoft Xbox 360 consoles, often designed originally for recreational purposes. Thus far, both types of VR systems have been exploited in different studies investigating the efficacy of VR in upper limb rehabilitation (Subramanian et al., 2020). Some studies have also adapted commercial gaming systems and specifically added games that were designed for rehabilitation of stroke patients (Aşkın et al., 2018). In this respect, it has recently been suggested that the type of systems used may greatly influence the results of motor recovery. In their meta-analysis, Maier et al. (2019) concluded that therapy with specialized VR systems leads to a higher beneficial impact on recovery, body function and on activity than CT, whereas non-specialized systems do not render the same outcome. Tailor-made systems designed to be used by patients with upper limb impairments appear to be a more viable tool to deliver effective motor rehabilitation, compared to off-the-shelf systems that were designed for healthy users.

The literature also suggests that VR systems, in particular specialized ones, can integrate multiple principles of neurorehabilitation in the therapeutic protocols and help manipulating practice conditions, in order to optimize motor learning and neuroplasticity processes. More specifically, task-specific practice, increase of difficulty level, variety of tasks with different goals, avatar representation or promoted use of the affected limb are key principles that can be particularly exploited for VR therapy (Maier et al., 2019). They can also contribute to the development of novel techniques for upper limb rehabilitation like the Reinforcement-Induced Movement Therapy that includes a VR-based training and aims to promote the use of the paretic limb for motor recovery (Ballester et al., 2016).

One major feature of VR systems is that they can typically deliver explicit and implicit feedback during therapeutic training, to a larger extent than in CT (Maier et al., 2019). Feedbacks can be delivered in different forms and provide information to patients on their movements, their performance and their results in real time, while they interact with the virtual environment during entrainment. Examples of multisensory feedbacks include: an on-screen avatar representing the patient's arms and hands, display of scores and records attained, or acoustic signals to provide information on the correct execution of a movement (Kiper et al., 2018; Rogers et al., 2019). As an example, a virtual environment with reinforced and frequent feedback was reported to have an added therapeutic effect as compared to CT, with a better motor recovery outcome in stroke patients (Kiper et al., 2018). Recent VR systems developed for rehabilitation purposes, such as the Elements system, were designed to specifically provide augmented feedback. Rogers et al. (2019) observed that patients receiving therapy with the Elements system experienced greater improvements in upper limb function than controls. Providing more feedbacks in order for patients to have more knowledge on their results and their performance during a single session, in real time, may help promoting motor learning in upper limb rehabilitation. As feedback can be provided simultaneously when using VR, it may also induce a more active participation from patients, associated with an increased motivation to succeed in the activities (Kiper et al., 2018; Rogers et al., 2019).

Increased participants' motivation is a recurring observation in studies. VR-based therapy appears to be more appealing to stroke patients. Several studies have included safety and technology acceptance evaluations in their protocols and found positive assessments in regards to acceptance and motivation, with patients reporting augmented motivation and willingness to pursue VR training at hospital, or at home (Burdea et al., 2019; Perez-Marcos et al., 2017; Warland et al., 2019). The qualitative substudy conducted by Pallesen et al. (2018) highlighted multiple factors that influenced patients' motivation in Brunner et al. (2017) clinical trial: the playful nature of the activities, the ability to progress in the games depending on their abilities, as well as the reward and feedback systems integrated in the VR solution. These factors may contribute to patients' motivation as they make therapy sessions more challenging and the perception of their improvements is facilitated throughout the treatment duration.

Patients' satisfaction is also often reported as very high after VR sessions (Demers et al., 2019; Lee et al., 2020). More precisely, the variety of activities in virtual environments, performing exercises in the form of games and the possibility of training in an enriched environment make VR-based therapy enjoyable to patients and possibly more engaging than CT (Wang et al., 2017; Hung et al., 2019; Rogers et al., 2019). Importantly, motivation and engagement in rehabilitation are related to compliance and adherence to therapy (Perez-Marcos et al., 2017). As a result, higher levels of motivation induced by VR-based therapy are likely to positively influence rehabilitation outcomes and lead to significant improvements in upper limb function. Also, therapists can establish a rehabilitation program that matches their patients' needs and preferences using VR systems settings (Kim et al., 2018; Hung et al., 2019). We conclude that since VR-based therapy has been established to be motivating to patients and associated with high adherence to therapy, it constitutes a viable tool to strongly encourage patients to exercise independently and frequently in the hospital and upon discharge, at home.

## Virtual Reality: A Patient-Centered Tool

VR systems are now often equipped with motion capture technologies such as the Leap Motion hand tracking device (Wang et al., 2017) or the Microsoft Kinect (Aşkın et al., 2018), which can track patients' movements and be used to gather data in regards to performance, kinematics and help provide an analysis of movement quality (Perez-Marcos et al., 2017). While this allows for clinicians to be able to track their patient's performance throughout entrainment, which is particularly advantageous if we consider a home-based rehabilitation, motion tracking solution also offers the opportunity to further individualize the clinician's intervention. Data can be used by therapists for a better assessment of each patient's abilities, to track their progression and more importantly, to adapt their intervention at every step of the rehabilitation process to ensure it matches the patient's needs and their goals. Adjusting the difficulty level of exercises is possible within multiple VR systems, making it possible to offer an intervention that is tailored to each patient's abilities, preferences and motor function level when training with VR (Hung et al., 2019; Kim et al., 2018). Using an artificial intelligence (AI) module, the novel BrightBrainer VR system used in Burdea et al.'s study (2019) changed game difficulties based on a patient's prior performance during tele-rehabilitation. Depending on the system used, therapists can specifically choose the focus of the exercises. Manipulation, hand grasping, whole-arm movement, pronation-supination or bimanual coordination are among the movements that can be selected by therapists to tailor each patient's exercise program (Brunner et al., 2017; Kiper et al., 2018; Schuster-Amft et al., 2018). VR systems designed for rehabilitation can also integrate modules that automatically adjust the difficulty of a task according to a patient's performance, as in the Rehabilitation Gaming System (RGS) (Cameirão et al., 2011). By capturing specific features of a user's upper limb, the system can adapt a task's parameters to an individual's abilities, allowing for further individualization of the therapy (Cameirão et al., 2010).

When focusing more particularly on how rehabilitation is conducted, VR therapy could also prove to be a safe tool for patients. The practice of ADL is possible in virtual environments, with a wide range of ADL proposed such as grocery shopping or crossing a street (Adams et al., 2018). Thus, VR systems allow therapists to propose tasks that would possibly be unsafe if performed in the real world (Laver et al., 2017). For example, practicing a cooking activity in a virtual environment would remove the risk of burns.

## Ecological Validity of Virtual Reality in Therapy

In VR-based therapy, patients interact within a virtual environment that can simulate daily life situations and reproduce, to different levels of realism, the real world. As a result, VR-based training may offer an almost naturalistic, ecologically-valid environment. Owing to these features, VR systems may facilitate accessibility to the practice of ADLs during patients' stay at the hospital, as it is not always feasible within a hospital facility. The effectiveness of ADL-focused therapy is already established in upper limb rehabilitation but VR may add advantages to ADL-focused interventions (Legg et al., 2007). Specific VR systems enable task-oriented practice in virtual worlds in order to reacquire functional skills through different activities such as cooking, gardening or grocery shopping in a virtual world (Adams et al., 2018; Aşkın et al., 2018). As an example, practicing virtual ADL with the SaeboVR system designed for upper limb rehabilitation was associated with significant improvements in motor function measures of chronic stroke patients in Adams et al.'s study (2018). In addition, the practice of ADL that are particularly meaningful and relatable to the patient can contribute to an increased adherence to the treatment and increased motivation to pursue rehabilitation (Adams et al., 2018).

However, even if the practice of ADL in a virtual environment is now feasible, with significant improvements observed, it has yet to be determined if gains of VR training do translate to improved performance of real-life activities in the long term. Evidence of the transfer of VR training effects to ADL for patients who suffered a stroke is still limited (Aminov et al., 2018). Long-term follow-up studies are necessary to assess more carefully the effect of VR-based therapy on independence in ADL following discharge. Effects of VR-based tele-rehabilitation on ADL also remain to be evaluated.

## Limits of Using Virtual Reality in Rehabilitation

There are some limitations that have been noted concerning VR. Using VR as a rehabilitation tool may be accompanied by some relatively minor adverse effects that may stem from the equipment used and prolonged exposure to a screen while doing different exercises and movements. A few cases of motion sickness, headaches or soreness have been reported by patients in studies (Hung et al., 2019; Perez-Marcos et al., 2017). However, these are rare, and most patients who participated were not subject to any major adverse event over the course of their treatment (Aşkın et al., 2018; Norouzi-Gheidari et al., 2019; Wang et al., 2017), even when using a head-mounted display for a fully immersive VR experience during multiple sessions (Lee et al., 2020).

VR-based therapy is also very dependent on the proper functioning of the equipment. Frequent device malfunctions such as screen freezing, inaccuracy of movement tracking or communication problems can occur in the middle of an activity and be associated with frustration or decrease in motivation, which may reduce the benefits of the treatment (Burdea et al., 2019; Pallesen et al., 2018).

## Suggestions Regarding the Use of Virtual Reality in Clinical Settings

Following this review, we suggest some recommendations can be made regarding the use of VR for the rehabilitation of the upper limb for stroke patients. While VR appears to be a suitable tool for rehabilitation, using VR as an adjunct, combined with conventional occupational and physical therapy, may be more beneficial for the recovery of upper limb function rather than relying on VR alone (Kiper et al., 2018; Wang et al., 2017). In addition, therapists should exploit specific VR systems features such as augmented feedback, gamified and motivating activities, movement tracking, practice of virtual ADLs and the possibility of training in an environment similar to the real world as they may help enhancing functional outcomes in upper limb rehabilitation and optimize their intervention (Adams et al., 2018; Maier et al., 2019; Pallesen et al., 2018; Rogers et al., 2019). Also, current evidence comfort us in suggesting that specialized VR systems, specifically designed for upper limb rehabilitation, are to be preferred (Aminov et al., 2018; Maier et al., 2019). Specialized VR systems are indeed more effective and offer flexible patient-based tailoring to therapists. But specialized VR equipment is not yet widely available in clinical settings and its expensive cost may, in some circumstances, constitute a barrier to the development of its use in rehabilitation clinics.

## Perspectives on the Future of Virtual Reality in Clinical Settings and Research

One major development regarding the use of VR in the recent years is the immersive feature of some VR systems. Immersion refers to the sensorimotor coupling between the user and the virtual environment provided by the system, and determines the potential of a VR system to effectively isolate a user from the real world (Mestre, 2015). Fully immersive systems place users in an environment that integrates 3D images and objects, where they have no access to the real world and are only exposed to sensory feedbacks coming from the system itself. In contrast, non-immersive VR systems generally display a virtual environment on a screen that users interact with using devices such as keyboards, controllers or joysticks, letting users experience both the real and virtual world at the same time (Huang et al., 2019; Kilbride et al., 2018). Non-immersive systems are more common in rehabilitation settings and have been predominant in VR studies until recently. However, with head-mounted display technologies becoming more and more popular, immersive VR can now become more widespread. It is suggested the level of immersion of a given VR system might play a role in motor recovery, although it is still unclear how exactly (Adams et al., 2018). Fully immersive VR therapy may enhance the feeling of immersion, enabling an even more engaging experience and facilitating patients' performance when executing movements with their impaired upper limb, especially as they can provide more realistic virtual environments. More specifically, immersive properties of virtual environments are associated with the notion of presence, that refers to the feeling of being inside the virtual world. The feeling of presence enables participants to behave in the virtual environment as if it was the real world (Mestre, 2015). Only few studies have investigated fully immersive VR with the use of head-mounted displays such as the HTC Vive, whose spatiotemporal resolutions complies with this sort of behavioral applications (Verdelet et al., 2019). They have reported significant improvements in upper limb function and performance in ADL after multiple therapy sessions (Ögün et al., 2019; Lee et al., 2020; Mekbib et al., 2020). More studies are nevertheless needed to assess the effectiveness of immersive VR-based therapy for the recovery of upper limb motor function, to determine if fully-immersive systems are more effective than non-immersive ones at short- and long-term. Future studies on immersive VR systems may provide better insights into how the level of immersion influences neuroplasticity and cortical reorganization in stroke patients, what mechanisms are at work, and how to better integrate VR in upper limb rehabilitation for stroke patients (Ahmed et al., 2020). As this technology is becoming more widespread, it is likely that immersive VR systems will take on an important part in future rehabilitation.

When considering research on VR as a rehabilitation tool more globally, additional clinical studies are needed with larger samples of patients in order to gather stronger evidence of VR efficacy. It is also necessary to further investigate effects of VR-based therapy in the longer term. Results of follow-up studies will give a better understanding on the retention of the motor learning acquired during treatment with VR.

For VR to become a viable therapy tool, it is also important that research focuses on identifying what the "ingredients" for effective VR are, as well as the conditions whereby VR can be best used, to maximize its potential. Studies investigating effectiveness of VR have applied different experimental designs in terms of frequency (ranging from two to five sessions a week), duration of training sessions (30–60 min) and length of treatment (from 4 to

12 weeks). Since it has been suggested that a higher dose of training volume is preferable, with more than 15 h of total intervention time (Laver et al., 2017), future studies are needed to determine if the dose of VR-therapy does have a significant effect on motor rehabilitation outcomes and if so, which dosage has to be applied when implementing VR in therapy. Future studies will also help specify the effects of timing of VR interventions on functional outcomes and thus, may help determine the optimal timing during which VR interventions can lead to significant improvements in stroke rehabilitation (Merians et al., 2020).

There are also several open questions concerning the patients who can use and benefit from VR therapy, regarding factors such as the severity of the motor impairment or the lesion topography. Kiper et al. (2018) observed that a VR intervention was effective after both hemorrhagic and ischemic stroke, suggesting that stroke etiology does not influence therapy outcomes differently. But further studies are still necessary to determine the population that can best benefit from VR therapy. In addition, active rehabilitation is recommended early, in the subacute phase of stroke recovery, in order to maximize motor recovery gains. In VR research, few studies have been conducted with patients in subacute stage and chronic stage although improvements have been observed in both populations (Aminov et al., 2018), hence it is still necessary to identify the time window for applying VR therapy.

Not last, stroke patients can suffer from cognitive impairments on top of their motor deficits. Patients with severe cognitive impairment were often excluded from previous studies (Aşkın et al., 2018; Brunner et al., 2017; Kiper et al., 2018; Norouzi-Gheidari et al., 2019; Perez-Marcos et al., 2017; Schuster-Amft et al., 2018). However, there are now VR systems intended for rehabilitation of both cognitive and motor functions for stroke patients (Rogers et al., 2019), which broaden the target population and illustrate further the potential of VR for the treatment of major stroke sequelae.

## CONCLUSION

Severity of upper limb impairment following stroke is a predictor of poor functional hand ability (Wade et al., 1983; Lai et al., 2002) and a predictor of poor quality of life (Nichols-Larsen et al., 2005). Effective rehabilitation approaches are needed to enhance motor and functional recovery. Since VR has emerged as a suitable rehabilitation tool, VR interventions have shown to offer patients with intensive, repetitive and task-specific entrainment tools in naturalistic virtual environments. Recent evidence show that VR-based therapy combined with CT produce significant improvements in upper limb motor function in stroke patients. Beyond evidence of efficacy, VR systems appear to offer highly engaging and motivating activities to patients, in virtual environments that may be similar to the real world. They also present peculiar features such as movement tracking and the integration of key principles of neurorehabilitation including reinforced feedback. These elements may be advantageous to patients and clinicians, in order to enhance rehabilitation treatments but also to improve therapists' intervention and optimize single patient's tailored care, in the hospital and at a patient's home. Further studies are needed to maximize the potential offered by VR and to ensure it is used effectively as a therapy tool.

## AUTHOR CONTRIBUTIONS

JB and AF contributed to conception and organization of the research work. JB collected the literature materials and wrote the first draft of the manuscript. AF and JL critically revised the manuscript and added sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.