

Virtual reality in rehabilitation of patients after stroke

Virtuální realita v rehabilitaci pacientů po CMP

Abstract

Stroke is one of the most common causes of acquired disability. It represents a major socio-economic problem that can have a serious impact on different areas of life. Early and sufficiently intensive rehabilitation after stroke contributes significantly to optimal functional outcomes and improves the quality of life of the patients. New neurorehabilitation approaches based on technology and virtual reality (VR) make it possible to design individualized intensive rehabilitation training and improve motor learning through multimodal feedback. Rehabilitation in virtual reality is a highly motivating therapy with many benefits for the patient. It also increases patient compliance to therapy. It is a safe form of therapy and after proper education of the patient, the physical presence of a physiotherapist is not necessarily required. This makes the use of VR in home exercise and telerehabilitation possible. The aim of this review article is to provide up-to-date knowledge and brief information on VR-based neurorehabilitation after stroke, with emphasis on the medical device regulation (MDR)-certified VR interface, which was developed in collaboration between the University Hospital Ostrava and VR Life. We found that conventional rehabilitation combined with VR seems to be more effective than conventional physiotherapy and occupational therapy alone in the rehabilitation of patients after stroke.

Souhrn

Cévní mozková příhoda je jednou z nejčastějších příčin získaného postižení. Představuje závažný socioekonomický problém, který může mít závažný dopad na různé oblasti života. Včasná a dostatečně intenzivní rehabilitace po cévní mozkové příhodě významně přispívá k optimálním funkčním výsledkům a zlepšení kvality života. Nové neurorehabilitační přístupy založené na technologiích a virtuální realitě (VR) umožňují navrhnout individualizovaný intenzivní rehabilitační trénink a zlepšit motorické učení prostřednictvím multimodální zpětné vazby. Rehabilitace ve VR je vysoce motivující terapie s řadou výhod pro pacienta a zvyšuje také compliance pacienta k terapii. Představuje bezpečnou formu terapie a po náležitém edukování pacienta není nezbytně nutná fyzická přítomnost fyzioterapeuta. Díky tomu je možné využití VR v domácím cvičení a telerehabilitaci. Cílem tohoto přehledového článku je poskytnout aktuální poznatky a stručné informace o neurorehabilitaci po CMP založené na VR s důrazem na rozhraní VR certifikované nařízením o zdravotnických prostředcích (medical device regulation; MDR), které bylo vyvinuto ve spolupráci Fakultní nemocnice Ostrava a společnosti VR Life. Zjistili jsme, že konvenční rehabilitace v kombinaci s VR se zdá být při rehabilitaci pacientů po cévní mozkové příhodě účinnější než samotná konvenční fyzioterapie a ergoterapie.

Introduction

In the literature, 33–42% of patients require assistance with activities of daily living, such as personal and general hygiene, dressing, independent food intake, control of urination and defecation, and toilet use, 3–6 months after stroke. Of these patients, 36% have lasting effects 5 years after stroke. These effects are classified according to the

International Classification of Functions (ICF), Disability and Health at the levels of body functioning (any loss or abnormality of function, including neuropsychological function), activity (related to the individual's tasks and activities, e.g., as a consequence of disability in terms of functional performance), participation (involvement in life situations), and environment (the individual's disadvan-

tage resulting from impairment and disability, including disability and quality of life) [1]. In addition to sensorimotor deficits, more than 40% of stroke survivors develop cognitive impairment. Other sequelae caused by stroke are sensory disturbances, speech impairment, fatigue, depression, swallowing difficulties, gait disturbances, and impaired balance and coordination [2].

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Fig. 1. VR training in a hospital bed.

Obr. 1. Cvičení ve VR na nemocničním lůžku.

The general goal of neurorehabilitation is to improve activities of daily living and increase social integration. To promote neuroplasticity, early initiation of rehabilitation, a high number of repetitions (reps), and high intensity task-specific training are essential. However, training-based methods are often tedious, resource-intensive, and require specialized equipment or facilities [3]. The success of conventional rehabilitation requires both active participation in therapy and adherence to regular exercise in the home environment. The rehabilitation process may be prolonged if the patient loses interest or qualified therapists and technical equipment are lacking.

In this context, the combination of traditional (conventional) rehabilitation techniques with new technologies, such as robotics, brain-computer interfaces, non-invasive brain stimulators, neuroprostheses, and wearable motion analysis devices, may have a positive impact on cognitive and motor rehabilitation [4].

Methodology

A systematic bibliographic search of PubMed, SAGE Journals, and Cochrane databases was conducted for papers published between January 2016 and December 2023. Meta-analyses and systematic reviews that assessed sensorimotor deficits, balance,

cognitive impairment, speech, and impaired quality of life were selected based on select keywords: stroke, neurorehabilitation, virtual reality, neuroplasticity.

The essence of virtual reality

Over the past two decades, the professional community has turned to virtual reality (VR) and gaming approaches in an effort to address costs and increase patient engagement in the rehabilitation process [5]. VR is defined as “the use of interactive simulations created with computer hardware and software that allow users to engage with environments that look and feel similar to the real-world objects and events” [3].

VR therapy can be implemented through a fully immersive experience (i.e., full integration of the individual into the virtual environment through three-dimensional technology using a head-mounted display) (Fig. 1), a semi-immersive experience (i.e., three-dimensional technology using a high-performance graphical computer system coupled with a large surface area to display a visual scene without the use of a head-mounted display), or non-immersive (i.e., two-dimensional technology with a keyboard, mouse, motion sensors and other external devices) [6].

Through the simulated environment in VR, various forms of feedback, including internal (tactile, proprioceptive, and kinesthetic information) and external (visual and auditory), are provided in real time with immediate results, leading to enhanced experience and improved motor learning. VR enables the creation of individualized motor training with high levels of repetition and variability [7].

Virtual reality in neurorehabilitation

A seminal finding for the development of neurorehabilitation in the VR setting was the discovery of mirror neurons in large motor-related brain regions, including the supplementary motor area (SMA), premotor cortex, primary motor cortex, and cortical areas not primarily related to motor activity, including the middle frontal gyrus and superior and inferior parietal gyri [8]. Rizzolatti and Sinigaglia stated that the mirror mechanism is a fundamental principle of brain functioning. Mirror neurons are activated both when performing a particular motor action and when observing another person performing it [9]. Intervention in VR leads to improved in-

terhemispheric balance, with a shift in activation from the contralateral to the homolateral primary sensorimotor cortex during paretic limb movement, improved connectivity between different functional areas, increased cortical representation of the affected limbs, and increased activation of areas in the frontal cortex [10].

Hao et al. reviewed the literature identifying the effects of rehabilitation in VR to promote neuroplastic changes in individuals after experiencing stroke in acute, sub-acute, and chronic stages. Six of the studies were randomized controlled trials (RCTs), two were clinical studies, 11 were single-arm pre-post studies, and seven were case studies. A total of 24 studies focused on sensorimotor rehabilitation, and three of them focused on cognitive rehabilitation in patients with neglect syndrome. The VR intervention in each study was categorized into one of three categories according to the level of immersion: non-immersive (6 studies), semi-immersive (18 studies), and fully immersive (2 studies only). Functional MRI (fMRI), EEG, and transcranial magnetic stimulation (TMS) were used to measure neuroplastic changes. Each level of immersion in VR could induce significant changes in neuroplasticity. However, this systematic review had several limitations, including the sample size, 18 studies not having a control group, and heterogeneity in the tools used to assess neuroplasticity.



Fig. 2. Module "Hanging laundry".

A patient grabs laundry from a basket on the floor using both upper limbs. As soon as the patient puts the laundry up to the clothesline, it automatically attaches. The difficulty of the task depends on the height of the line and the range of motion for the upper limbs. Once a certain amount of laundry has been hung, the line is "cleaned" and the task can be repeated.

Obr. 2. Modul „Věšení prádla“.

Pacient uchopí prádlo z koše na podlaze pomocí obou horních končetin. Jakmile pacient prádlo položí na šňůru na prádlo, automaticky se připevní. Obtížnost úkolu závisí na výšce šňůry a rozsahu pohybu horních končetin. Po zavěšení určitého množství prádla se šňůra „vyčistí“ a úkol lze opakovat.



Fig. 3. Module "Carrying mugs to shelves".

A patient has to grasp and transfer mugs from a drip tray to shelves of various heights. The patient also has to turn the mugs upside down. The difficulty can be increased by increasing the height of the shelves, rotating the handles of the mugs, and stacking the mugs according to colour and size.

Obr. 3. Modul „Přenášení hrnků do polic“.

Pacient musí uchopit a přenést hrnky z odkapávací misky na police různé výšky. Pacient musí hrnky otočit dnem vzhůru. Obtížnost lze zvýšit zvětšením výšky polic, otáčením úchytů hrnků a skládáním hrnků na sebe podle barvy a velikosti.

Examples of neurorehabilitation in immersive VR developed by our team are shown in Fig. 2 and 3. However, other possibilities are robotic interfaces or commercial gaming systems [11]. One meta-analysis demonstrated a greater effect of VR in post-stroke patients in improving upper limb function and activity than conventional rehabilitation [12].

Comparison of conventional rehabilitation and virtual reality rehabilitation

The studies conducted thus far have focused on several aspects regarding the effectiveness of VR in rehabilitation after stroke, primarily motor deficits, especially in the upper limb, as well as gait and balance disorders. In a 2019 meta-analysis of 38 studies evaluating the effectiveness of VR- and play-based interventions on improving upper limb function after stroke, nearly 29% improvement was demonstrated, particularly in the acute and sub-acute stages after stroke (< 6 months). A significantly greater effect was demonstrated for game-based interventions compared to virtual systems that lacked a game component and provided only simple feedback. In contrast to expectations, there was no greater improvement with higher dosages (i.e., number of repetitions per task and task execution time) [5].

A 2020 study reported conflicting evidence regarding the timing, dosage, and method of application of increased dose of robotics, VR, or repetitive exercise and suggested examining both high-volume training and a specific method of rehabilitation training in VR during the first months after stroke. The aim of the study was to empirically test unanswered questions regarding the parameters of high-dose intensive training and optimum timing of intensive robotic motor training in the first 2 months after stroke, particularly on improving hemiparesis and hand function [13].

The aim of a 2019 systematic review and meta-analysis in patients with chronic stroke (> 6 months) was to determine whether VR training is effective at improving upper limb, lower limb, and overall functional ability. A total of 21 studies with 562 participants compared groups with and without VR rehabilitation. Rehabilitation training in VR improved lower limb functions, including balance and gait, to a similar extent as upper limb functions, and also improved the overall functional ability. Relatively strong effects on muscle tension and muscle strength were

observed, with moderate effects on activities of daily living, joint motion range, gait, balance, function, and kinematics. However, the number of studies included in the analysis examining the effect of VR on activities of daily living was relatively small [3].

A 2020 systematic review and meta-analysis of 32 studies (20 randomized and 12 non-randomized) involving a total of 809 subjects evaluated spatiotemporal gait parameters during VR training and compared it to conventional gait therapy. The meta-analysis also investigated whether combined VR and robotic-assisted rehabilitation (RAR) gait training was superior to VR or RAR gait training alone. The analysis showed evidence of a greater effect of VR gait training, which was evident in all spatiotemporal gait parameters, including walking speed, step frequency, and stride length (moderate effect size increase) [14].

One neuroimaging study published in 2017 found that a more pronounced improvement in gait performance after training in VR was associated with greater activation of brain regions associated with motor planning and execution, specifically activation in the somatosensory-motor cortex and SMA. Many of the included studies reported improvements in static and dynamic balance, specifically improvements on the Berg Balance Scale, Timed Up and Go test, and Functional Reach Test, with VR use. Moderate to large standardized effects of VR therapy on walking speed, stride length, and step frequency were found when VR was combined with RAR [15].

A 2016 meta-analysis of 16 randomized trials with 428 participants demonstrated significant improvements in the Berg Balance Scale and Timed Up and Go test in post-stroke patients who received VR rehabilitation compared to those who did not participate in VR rehabilitation [16].

A systematic review and meta-analysis from 2021 included 73 studies with 1,617 participants (819 in the VR group and 798 in the control group) and showed that VR improved motor skills, including gait, balance, sensory, and cognitive impairments. Patients enrolled within the acute phase of stroke did not show significant differences in the areas stated above when compared to the conventional rehabilitation groups. However, patients enrolled 6 months after stroke demonstrated improvement in functional abilities (i.e., gait velocity, functional balance, stride length, and cadence). How-

ever, many of the included studies produced only neutral results (i.e., VR intervention had similar benefits to conventional therapy) or found no significant benefit of VR relative to conventional rehabilitation. Possible explanations include the heterogeneity of studies, different definitions of conventional rehabilitation protocols, slow recruitment rates, and the inclusion of patients in the chronic phases of stroke, when the recovery is slower [1].

A systematic review and meta-analysis published in 2020 summarized the evidence on the effectiveness of immersive, semi-immersive, and non-immersive VR exercise in improving cognition after stroke. A total of 8 RCTs with 196 participants were included. The meta-analysis did not provide evidence that the VR interventions were more effective than conventional rehabilitation in regard to improved global cognition, attention, memory, and language. Limitations of the meta-analysis include relatively few studies, higher heterogeneity, and selection bias, making it impossible to conduct analyses to detect differences between the VR subtypes, intervention parameters (frequency, session length, total duration), or by different cognitive domains (global cognition, attention, memory, visuospatial skills, executive function, and language) [6].

Use of virtual reality after stroke

Rehabilitation training in VR can start as early as in the stroke units. Based on an individual assessment of the patients' clinical condition, VR programs can be applied starting with less demanding ones, such as relaxation and breathing programs. A 2021 review of the scope of use of VR in ICU care addressed the use of VR for relaxation, delirium, and sleep [17]. A relaxation program in VR was found to significantly reduce anxiety, pain, heart and respiratory rates, and arterial pressure in patients. In rehabilitation aftercare, such as inpatient rehabilitation wards and aftercare facilities, more challenging programs in VR can be used for rehabilitation training, which must be individualized and tailored to the therapeutic goals. For example, activities and situations that the patient encounters in everyday life can be trained or a cognitive task can be added.

Other uses of virtual reality in neurorehabilitation

VR also finds applications in neurorehabilitation for other diagnoses. The second

most common diagnostic group addressed in studies is Parkinson's disease. Study results report greater improvements in balance [18–21], stride length [19,21], quality of life, activities of daily living [20,21], and alleviation of depressive symptomatology [20] compared to conventional rehabilitation. In patients with multiple sclerosis, VR is effective in reducing fatigue and improving quality of life [22], and it also reduces fear of falling [23]. Rehabilitation programs for children with cerebral palsy (CP) using VR can improve children's functioning and performance in activities of daily living [24,25], upper and lower limb mobility, and cognitive abilities [25]. A meta-analysis evaluating the efficacy of VR-based vestibular rehabilitation in patients with peripheral vestibular disorders found potential clinical benefit compared with conventional vestibular rehabilitation therapy, with improvements in subjective measures and posturography [26]. Other studies have demonstrated improvements in cognitive function, performance of activities of daily living, and reductions in anxiety and depressive states in patients with acquired brain injury [27]. A beneficial effect of rehabilitation in VR or associated with conventional rehabilitation has been observed in spinal cord injury conditions, with improvements in motor skills, balance, aerobic function, and pain reduction [28]. Studies investigating the application of virtual reality for neuropathic pain management in people with spinal cord injury have found VR to be an effective analgesic intervention with short-, medium-, and long-term effects, particularly when combined with transcranial direct current stimulation [29]. Rehabilitation interventions in VR may also have applications in neuromuscular diseases, such as Duchenne muscular dystrophy to improve patients' training performance [30].

Aspects of rehabilitation in virtual reality in terms of cost and availability analysis

We found 10 virtual reality rehabilitation projects within the EU that have been certified according to the MDR. Four projects are dedicated to neurorehabilitation.

Living Brain with the TEORA[®] MIND (Heidelberg, Germany) product focuses mainly on cognitive occupational therapy training in the context of routine household chores. They use Pico 4 (ByteDance, Beijing, China) VR glasses as HW, they use controllers. VR

LIFE with VR Vitalis[®] Pro focus on physical, cognitive and psychological rehabilitation in different types of modules. Unlike others, they also use modules for the lower limbs. The modules are designed for exercises with controllers and some without (especially for fine motor skills). The price of the annual licence is EUR 4,060 per year. The price of the HW box is EUR 1,400. It includes the Oculus Quest (Meta, Irvine, CA, USA) 2 VR glasses, tablet, strap with spare battery, leg holders, silicone covers for the controllers and router including charging station. Cureosity focuses on upper limb and cognitive rehabilitation with the CUREO[®] product (Düsseldorf, Germany). Some modules are designed for exercise with controllers and modules for fine motor skills without controllers. The price of the complete HW box set and unlimited time license is EUR 36,000. The box includes the Oculus Quest 2 VR glasses, tablet, charging station and router. VR Medical focuses on upper limb and cognitive function with the VR rehabilitation product. The modules are trained without controllers. The price of the HW box with Oculus Quest 2 VR glasses, tablet and router is EUR 1,000 and the annual license of the app is approximately EUR 4,800.

The selection of the type of VR goggles most suitable for the use in rehabilitation was made according to the following parameters: safety, availability, price, ease of use, weight, graphics, performance and limb connectivity. VR glasses with PC connectivity were compared. These scored high in graphics, performance and limb connectivity and conversely scored very low in safety, price and ease of use. Next for comparison were the so-called mobile phone mounts, which scored high in terms of accessibility and security, but do not allow for limb connection. The best performers were wireless goggles like Oculus Quest or Pico 4, which came out high in safety, accessibility, ease, limb involvement, and had only poor graphics and performance.

For rehabilitation, it is important to have additional accessories to the VR goggles, such as a tablet or other display device on which the therapist is able to monitor what the patient can see and guide them. In addition, it is often necessary to have an external router for a stable connection to the internet (for example, for image transmission). A strap with a spare battery is often recommended to balance the weight of the VR glasses on the patient's head, putting less strain on the cervical spine. Silicone covers

for the controls (if the application uses them) that fit better on the patient's hand and do not slip, and possibly a device that allows sensing of lower limb movements. Everything must be well disinfected.

Rehabilitation applications in virtual reality are not used long enough to have enough data for cost-effectiveness analysis. So far, we have found that patients in intensive care units and anaesthesia-resuscitation wards with respiratory problems can stay in the acute bed for a shorter time, sometimes up to one-third of the time. VR can also be used to fully exercise several patients at once, where patients are "guided" by virtual reality and the therapist adjusts and controls them. This is not yet possible with subacute patients after stroke in neurology, where more supervision is needed.

Conclusion

VR has great potential to become a common component of neurorehabilitation programmes in patients after stroke, including acute and post-acute post-stroke rehabilitation. Its efficacy has been studied at different stages after stroke and in different age categories. VR represents a safe and motivating form of therapy with many benefits with continuing development of VR software, interfaces, and exercise protocols. For example, a realistic environment could be created that allows practice by simulating real-life activities of daily living and situations that, in the real world, would pose a higher risk of injury or falls.

An important prerequisite for the effectiveness of VR rehabilitation is the selection of appropriate patients, who must, among other things, actively cooperate and be motivated to exercise. Future patient-oriented research on VR rehabilitation after stroke must target both acute and sub-acute stages of stroke. Protocols must include a well-defined study design and parameters, such as conventional rehabilitation protocol(s) and timing, VR protocol, frequency, intensity and duration of rehabilitation training in VR, including type of VR, and combination with other modern neurorehabilitation modalities (e.g., mirror therapy, focal application of vibration, constraint-induced movement therapy).

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Conflict of interest

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