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Virtual reality in rehabilitation of patients after stroke

Virtuální realita v rehabilitaci pacientů po CMP

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Š. Baníková[1,2], A. Najsrová[1,2], I. Fiedorová[1,2], J. Trdá[3], O. Volný[1,2]

[1] Department of Neurology, University Hospital Ostrava, Czech Republic
[2] Centre for Clinical Neurosciences, Faculty of Medicine, University of Ostrava, Czech Republic
[3] VR LIFE Ltd., Ostrava, Czech Republic

Assoc. Prof. Ondřej Volný, MD, PhD
Centre for Clinical Neurosciences
Faculty of Medicine
University of Ostrava
Syllabova 19
703 00 Ostrava
Czech Republic
e-mail: ondrej.volny@fno.cz

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Abstract
Stroke is one of the most common causes of acquired disability. It represents a major socioeconomic 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 VR 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.

Souhrn
Cévní mozková příhoda je jednou z nejčastějších příčin získané disability. Představuje závažný socioekonomický problém, který může mít závažný dopad na různé oblasti života. Včasná a dostatečně intenzivní rehabilitace po CMP významně přispívá k optimálním funkčním výsledkům a zlepšení kvality života pacientů. 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 na MDR (medical device regulation) certifikovaný VR rehabilitační zdravotnický prostředek, který byl vyvinut ve spolupráci FN Ostrava a společnosti VR Life.

Key words
stroke – neurorehabilitation – virtual reality – neuroplasticity

Klíčová slova
CMP – neurorehabilitace – virtuální realita – neuroplasticita

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 disadvantage 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].

Fig. 1. Virtual reality training in a hospital bed.
Obr. 1. Cvičení ve virtuální realitě 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, 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, noninvasive 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 defined keywords: stroke, neurorehabilitation, virtual reality, neuroplasticity.

Definition of VR

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].

Virtual reality 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 also enables the creation of individualized motor training with high levels of repetition and variability [7].

VR 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 interhemispheric 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 stroke in acute, subacute, 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 some limitations including limited sample size, missing control group (18 studies) and differences in tools used in neuroplasticity assessment.

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.

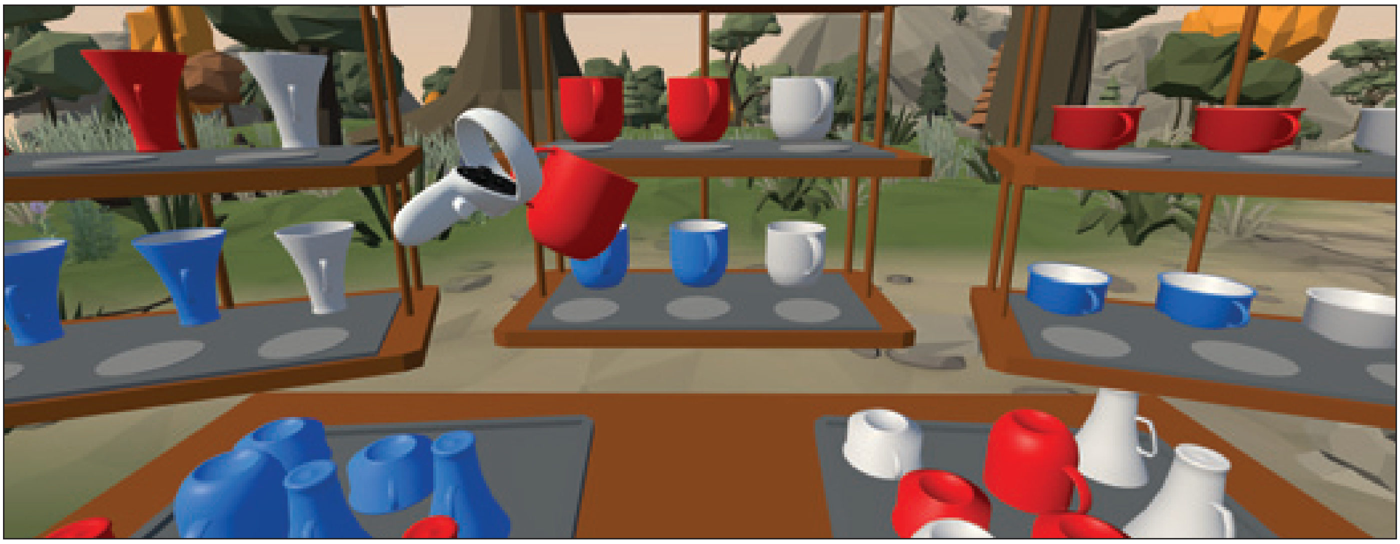

Fig. 3. Module "Carrying mugs to shelves".

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 také 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].

Conventional rehabilitation vs. rehabilitation in VR

The studies conducted so far have focused on several aspects regarding the effectiveness of VR in rehabilitation after stroke, primarily on motor deficits, especially of the upper limb, as well as on 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 subacute stages after stroke (< 6 months). A significantly greater effect was demonstrated for game-based interventions compared to virtual systems that lacked a gaming 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 testing of 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 of participants in chronic phase of stroke (> 6 months) was to determine whether VR training was effective at improving the upper and limbs functions, 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, 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 very 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). However, many of the included studies demonstrated only neutral findings (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 a limited number of high-quality studies, higher heterogeneity, selection bias (making it impossible to conduct analyses to detect differences between particular VR subtypes, different intervention parameters or by different cognitive domains) [6].

Use of VR in rehabilitation after stroke

Neurorehabilitation in VR after stroke might be initiated as early as possible (after 24 h). 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 scoping review of VR use at intensive care units (ICUs) has addressed the use of VR for relaxation, delirium prevention, and quality of sleep [17]. A relaxation program in VR was found to significantly reduce anxiety, pain, heart and respiratory rates, and arterial pressure. In rehabilitation aftercare, such as inpatient rehabilitation units or 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 specific cognitive tasks might be added.

VR rehabilitation in other neurological diagnoses

Virtual reality 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]. Beneficial effects of VR rehabilitation or associated with conventional rehabilitation has been observed in spinal cord injury, with improvements in motor skills, balance, aerobic function, and pain reduction [28]. Studies investigating the application of VR 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 [30].

MDR-certified VR tools for post-stroke rehabilitation

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

Living Brain with the TEORA® MIND (Heidelberg, Germany) product focuses mainly on cognitive occupational therapy training. They use Pico 4 (ByteDance, Beijing, China) VR glasses as hardware (HW) with controllers. VR LIFE with VR Vitalis® Pro focuses on physical, cognitive and psychological rehabilitation in different modules. Unlike others, this VR tool uses modules for lower limbs rehabilitation. 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. 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 using controllers, while others focus on fine motor skills without the use of 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 functions with their VR product. Their modules are designed for exercises 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 is EUR 4,800.

The selection of the most suitable type of VR goggles for the use in rehabilitation was based on the following criteria: safety, availability, price, ease of use, weight, graphics quality, performance, and limb connectivity. VR goggles with PC connectivity were evaluated first, scoring high in graphics quality, performance, and limb connectivity, but very low in safety, price, and ease of use. Next, mobile phone mounts were assessed; they scored high in accessibility and safety but did not support limb connectivity. The best performers were wireless goggles, such as Oculus Quest or Pico 4, which rated highly in safety, accessibility, ease of use, and limb involvement, though they had an only moderate graphics quality 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 monitors what the patient can see and guide him/her. In addition, it is often necessary to have an external router for stable internet connection. 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, if possible, a device that allows sensing of lower limbs movements.

Rehabilitation applications in VR are not used long enough to have sufficient data for cost-effectiveness analysis. Thus far, we have found that patients in ICUs with respiratory problems tend to have shorter stays in acute care beds. VR can also be utilized to simultaneously exercise multiple patients, with VR providing guidance while a therapist adjusts and controls the exercises. However, this approach is not feasible for patients in the subacute phase of stroke, where an individual approach and increased supervision are required.

Conclusion

VR has a great potential to become a common component of neurorehabilitation programmes in patients after stroke. VR represents a safe and motivating form of therapy with many benefits and ongoing development of VR software, interfaces, and exercise protocols. For example, a very realistic environment allowing practice by stimulating real-life activities of daily living and also situations that, in the real world, might pose a higher risk of injury or falls might be created and customized.

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 subacute 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 approaches (e. g. RAR, mirror therapy, focal application of vibration, constraint-induced movement therapy).

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Conflict of interest

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