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Combined methods of rehabilitation of patients after stroke: virtual reality and traditional approach

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Abstract

OBJECTIVES: The aim of the research was to verify the possibilities of using virtual reality in combination with classical approaches to the rehabilitation of patients after stroke.

MATERIAL AND METHODS: As part of rehabilitation, we examined the possibilities of rehabilitation of the upper, lower limbs and fine mobility of the upper limbs in a selected group of patients that met the criteria for inclusion in a combined rehabilitation program using virtual reality with a focus on testing different approaches, devices and applications. At the same time, we tried to identify quantitative and qualitative parameters that could be objectively measured and based on them to evaluate the progress of patients in rehabilitation or in personalizing individual rehabilitation scenarios.

RESULTS: In patients who underwent a combined method of rehabilitation, we observed progress in the development of their ability to improve motor skills. We identified various categories of parameters that can be evaluated by artificial intelligence methods, and we also identified that the key elements in the use of virtual reality as a rehabilitation method are the so-called "WOW" effect and the creation of an emotional change in the patient that motivates him to rehabilitate.

CONCLUSION: We have shown that virtual reality methods have the potential to accelerate rehabilitation and increase the motivation of selected groups of patients after stroke.

Abbreviations:

VR - Virtual Reality
AR - Augmented Reality
CT - Computer Tomography
NMR - Nuclear Magnetic Resonance
COVID-19 - Coronavirus Disease 2019
3D - Three dimensional
COPM - Canadian Occupational Performance Measure
VRRT - Virtual Reality Reflection Therapy
WRA - Walking robot aids
TUG - Timed Up and Go test

ORIGINAL ARTICLE

INTRODUCTION

The situation of patients after a stroke in Slovakia as well as in Central Europe is very similar. The number of stroke deaths in Slovakia and the Czech Republic has been steadily declining since 1995, faster than other diseases (e.g. ischemic heart disease). The proportion of stroke in total mortality is decreasing, increasing the number of patients with recommended rehabilitation (Bruthans, 2019). Rehabilitation of patients after a stroke is one of the key elements in restoring their mobility and in many cases of returning to normal life, as confirmed by the following research and studies.

A total of 1383 publications were obtained from the two publication databases LILACS and PUBMED, which showed connections such as "rehabilitation", "virtual reality exposure therapy" and "video games" published between 2011 and 2018 (Aramaki *et al.* Apr. 2019). The most important 13 publications were processed in the conclusion, which pointed mainly to the possibilities of using the VR through games. The sample size of patients varied from 5 to 47 adults with chronic stroke. Various video games were used on Nintendo (8) and Xbox (5) devices. The exercises were performed two or three times a week, with each session lasting from 30 to 60 minutes, from 2 to 12 weeks. The most frequently evaluated results were balance, motor functions of the upper limbs, quality of life and daily activities.

A total of 1667 studies showing "stroke" and "virtual reality" were obtained from the three publication databases OVID, PubMed and EMBASE (Lee *et al.* 2019). According to selected criteria, the 21 most important publications up to 2018 were processed, which used the design of a randomized controlled trial. In conclusion, the analysis of the studies found that the treatment of stroke using virtual reality requires at least 8 weeks. Furthermore, (Lee *et al.* 2019) they point out that VR has a beneficial effect on lower limb function in patients with chronic stroke. They recommend using it several times a week. VR training is especially useful for improving lower limb movement as well as strength and muscle tone of the lower limbs.

From the four publication databases MEDLINE, EMBASE, Science Direct and The Cochrane Library, studies on “exoskeletal robotics” applied by VR technologies, Augmented Reality (AR) and gamification from 2010 to 2017 were researched (Mubin *et al.* 2019). Exoskeletal-based studies that did not include VR, AR or games were excluded. The total number of studies was reduced to 30 publications, which also showed results in the form of improvement in the condition of patients from various therapies. This analysis showed that there was a general improvement in patients' motor function through new techniques for coupling to exoskeletons. This categorization of studies helps to determine the range of rehabilitation therapies that can be successfully arranged before home rehabilitation.

We divided the publications from these studies into three groups, using video games, special equipment and VR Headset aimed at rehabilitation of the lower and upper limbs. The following studies have played important experiences for our research:

1. An experimental group of 15 patients in Malaysia received 30 minutes of video games and 1.5 hours of standard physiotherapy (Singh *et al.* 2013). A control group of 13 patients continued for 2 hours of standard physiotherapy. Both groups received 12 treatment sessions: 2 hours of sessions twice a week for 6 weeks. Changes in physical function were assessed using the Timed Up and Go test (TUG), the 30-second Sit to Stand test, the timed walking test, the Barthel index, and static balance. Physiotherapy with virtual games was as effective as without it in sustaining the activities of everyday life. Similar evidence from the study supports the use of further VR training with the Xbox Kinect game system as an effective therapeutic approach to improve motor function during stroke rehabilitation (Park *et al.* 2017). A video game study of 10 patients after a stroke showed an improvement in their COPM performance and satisfaction score (Aramaki *et al.* Sept. 2019). Patients were more motivated to rehabilitate and their work performance improved.

2. In 2016, the authors applied a visual illusion method to a sample of 25 patients from South Korea to provide a wider field of view during exercise (In *et al.* 2016). Twenty-five chronic stroke patients were randomly assigned to the VRRT group (13) and the control group (12). Participants in both groups performed a conventional rehabilitation program for 30 minutes. The VRRT group also carried out the VRRT program for 30 minutes for 4 weeks. The control group performed a conventional rehabilitation program and a placebo VRRT program. Output measures included the Berg Balance Scale (BBS), the functional range test (FRT) and the Timed Up and Go test (TUG), postural deflection (for static balancing ability), and 10 meters of walking speed (10 mWV). The beneficial effects of VRRT on balance and gait in people with chronic stroke have been confirmed.

3. Walking robot aids (WRA) used to treat lower limbs (Calabro *et al.* 2017) show that virtual reality has proven to be a valuable tool for improving training in neurorehabilitation. Twenty-four patients with chronic phase ischemic stroke from Italy were randomized into two groups. One group performed 40 exercises with VR (WRA+VR), while the other group undertook the exercises without VR (WRA-VR). Results (clinical, kinematic and EEG) were measured before and after the robotic intervention. The WRA+VR group performed better than the WRA-VR in the Rivermead mobility index and in the Tinetti performance-oriented mobility assessment. The similar results of the research (Vostry *et al.* 2020) point to the fact, that combined therapy of robotic, psychomotor, and cognitive rehabilitation can have positive effect on, and be suitable

Tab. 1. Patients with stroke registered in Slovak republic

Year		Age						Summary
		0-24	25-44	45-64	65-74	75-84	85+	
2018	Patients with stroke	10	297	3 025	3 334	3 239	1 360	**11 265**
	of which ischemic	7	243	2 658	3 052	2 964	1 252	**10 176**
	haemorragic	3	54	360	266	256	98	**1 037**
2017	Patients with stroke	11	344	3 073	3 424	3 321	1 383	**11 556**
	of which ischemic	8	278	2 685	3 126	3 043	1 282	**10 422**
	haemorragic	3	65	371	284	261	96	**1 080**
2016	Patients with stroke	15	275	2 961	3 106	3 194	1 339	**10 890**
	of which ischemic	12	224	2 575	2 832	2 959	1 236	**9 838**
	haemorragic	3	50	356	254	226	97	**986**
2015	Patients with stroke	22	309	2 907	3 055	3 106	1 235	**10 634**
	of which ischemic	16	259	2 559	2 803	2 874	1 144	**9 655**
	haemorragic	5	49	338	241	217	91	**941**
2014	Patients with stroke	18	258	2 589	2 695	2 796	1 189	**9 545**
	of which ischemic	14	200	2 299	2 488	2 551	1 106	**8 658**
	haemorragic	3	54	282	199	229	77	**844**

(Source: NCZI, 2019)

as a treatment for patients after ischemic stroke. The article (Liu *et al.* 2019) describes some studies on cognitive diagnosis and training for the elderly, and puts forward some suggestions for current studies, that VR technology can be better applied to cognitive training.

In our research, we focused on the use of virtual reality in combination with traditional approaches to the rehabilitation of such patients and we focused mainly on the possibilities of interaction in the virtual environment together with other sensory perceptions. Utilization of modern approaches in the field of information and communication technologies shows new possibilities at various stages of the rehabilitation process.

Statistics

As a result of significantly more accurate diagnostics using CT and NMR (Ružický *et al.* 2020), there was a significant shift in the representation of individual stroke categories. In 2018, there were more than 11,000 patients in Slovakia in the register of hospitalized stroke, including transient cerebral ischemia (TIA). According to the basic specification, strokes accounted for 90.3% of ischemic strokes. Table 1 a show the number of patients with stroke according to age groups surveyed in 2014 - 2018 in Slovakia. In terms of age categories, patients in the range from 65 to 74 years still predominate, who in terms of percentage represent approximately 30% of all patients with stroke. All patients over the age of 65 represent up to 70% of all cases. (NCZI, 2019).

Our goal is to bring rehabilitation closer to the largest possible group of patients after a stroke with the best possible effect of curing brain disorders. For this reason, we also suggest tele-rehabilitation, which can be done by elderly patients from home. The language barrier between Slovak and Czech is not a problem for older patients, so the proposed exercises are the same in these languages for Slovak and Czech patients. We will monitor the situation as it changes after the end of the COVID-19 pandemic in Slovakia and the Czech Republic.

MATERIALS AND METHODS

Creating a complex rehabilitation program based on the traditional physiotherapy approach to rehabilitation, along with the opportunities provided by virtual reality, is a prerequisite for verifying the possibilities offered by this hybrid approach. In this type of rehabilitation, however, it is not possible to work with every patient; moreover, it is not possible to implement and prepare a universal solution.

Fig. 1. Virtual environment of one of the scenarios. Ball is assigned to the left controller. The path of the ball is calculated based on the speed of the controller as it moves by the user. The right controller displays a pointer to an object in the scene that can be interacted with.
(Source: own research)

We formulated the following research goals for the use of combined methods of rehabilitation of patients after stroke by using virtual reality:

1. Finding out whether it is possible to speed up or improve the process of rehabilitation of patients after stroke through virtual reality methods.
2. Finding out the impact of measuring quantitative parameters in the exercise of patients using virtual reality will help change the approach to the organization of exercise through tele-rehabilitation.

In this work, we focused on the results of examining two hypotheses:

- H1: Rehabilitation through virtual reality can contribute to a more effective process of rehabilitation of patients after stroke.
- H2: The measurement of quantitative parameters and their evaluation can contribute to the creation of more effective methods of tele-rehabilitation.

Patient selection and contraindications

For patients, it is necessary to indicate a combination of approaches individually based on their current state of health, degree of disability and ability to withstand the burden of the body that may arise using virtual reality methods. When selecting patients for whom such a method of rehabilitation is suitable, it is necessary to monitor their ability to orientate and maintain balance in the space, which could possibly be impaired when the patient is immersed in a virtual environment using virtual reality. Since within virtual reality one of the main prerequisites for perfect immersion is the ability of spatial perception, the patient needs to be capable of stereoscopic perception. This factor is key in terms of stereoscopic projection in head mounted displays. The inability of stereoscopic perception is a contraindication for the use of rehabilitation methods using virtual reality. Another contraindication is if the patient suffers from motion sickness. This situation excludes about 20% of healthy users from using virtual reality. It is even more necessary to monitor this possibility in patients after stroke. In creating a virtual environment and designing a way of interaction within virtual reality, we try to eliminate this phenomenon by tracking the position and orientation of the user in space (we track 6 degrees of freedom). Patients were selected for testing the possibilities of using virtual reality in rehabilitation based on a questionnaire. In the questionnaire, we asked patients about their ability of motorics in terms of movement of individual limbs, ability of fine motorics of upper limbs, sensory perception (including visual and hearing disorders) and mobility in the cervical spine area (the patient uses the 360 ° range of the scene in virtual reality, so it is necessary for the patient to be able to watch the entire space). The patient's experience with the device is an advantage, since it is possible to eliminate any difficulties in understanding the control, navigation and interaction system in the virtual environment. On the other hand, in this case, the so-called WOW effect, which evokes a relatively strong emotional response (positive or negative) to the virtual environment can be lost.

Based on these assumptions, we selected patients to test the hybrid approach to re-stabilization. Patients who participated in the testing were properly informed about the rehabilitation conditions, possible contraindications and signed informed consent for their inclusion in the hybrid rehabilitation access test program. Six patients (two for each scenario) meeting the required criteria were selected for the pilot phase of testing. Based on a neurological examination, an interview with a physiotherapist, a psychologist and virtual reality experts, various rehabilitation scenarios were indicated for their rehabilitation.

Fig. 2. Rehabilitation of fine motor skills of the upper limbs. The user's physical movement is shown on the left. On the right is a virtual scene with a virtual skeleton obtained using sensors rigged to the 3D hand model when using Blocks application for Leap Motion sensor.
(Source: own research)

Rehabilitation scenarios and ways of interaction

As part of the traditional approach, we rehabilitated patients in an emotionally positive environment multiplied by multi-sensory perceptions (fragrance, relaxation music, space lighting), which were the motivating elements for the positive adjustment of patients to physiotherapy. In terms of physiotherapy, we focused on therapy of disorders that occur in patients after stroke. The most common disorders are:

- sensory disturbances
- disorders of symbolic functions
- cognitive impairment
- limb movement disorders (central paresis)
- involvement of the cranial nerves (especially paresis of the oculomotor nerves, paresis of the facial nerve, etc.)
- surface, deep sensitivity disorders
- vestibular and cerebellar disorders

In the rehabilitation plan, we focused on posture training and active movement to support reflex postural mechanisms (postural stability and postural control), for patients with lower limb problems. Within physiotherapy, it is possible to apply methods based on change in the load of the paretic lower limb using the ALFA stabilometric platform and the assessment of dynamic balance using the Timed Up and Go test (TUG) to improve postural stability (Mašán, 2020).

Due to generalization and assimilation in cognitive processes, new movement patterns are created in patients. The basal ganglia and cerebellum play a major role in acquiring motor habits and skills (requiring the correct sequence and coherence of movements) and movement patterns. Memory recording can be transferred from one form to another (for example, gradual automation when driving a car). Thus, in the association and sensory areas, stimuli are not only created, recognized, combined, but also stored. Therefore, each memorized information changes our perception of other information a bit. Only those that repeat often, or have an emotional charge, are gradually stored in long-term memory. The current idea of the process of storing explicit memory is as follows: information from the environment flows into the brain through sensory (visual, auditory, somatosensitive) organs and pathways into the primary and secondary sensory cortical areas.

Association areas of the cerebral cortex combine information from individual sensory (visual, auditory, olfactory, taste, and somatosensory - representing touch, pressure, pain, and muscle information) and motor areas. The essence of the disorder is the inability to use sensory information to create an adequate movement plan and program (Králiček, 2011). Kinesiotherapy activation programs focus on the initiation of cognitive processes and motor abilities. Fitness training helps maintain muscle strength and stability. It is necessary to maintain and develop those functions that are still left to the patient that are intact or relatively unaffected. The individual exercises are aimed at stretching and subsequently strengthening the muscles of the cervical, thoracic, lumbar spine and the muscles of the upper and lower limbs. It is important to include exercises for practicing balance and coordination while sitting, standing and walking. Cognitive training must motivate patients. The training should include several visual and acoustic stimuli.

A different approach to rehabilitation can be implemented if the patient has a dominant or non-dominant side, while it is possible to focus on other types of exercise (especially the development of fine motor skills of the upper limbs). In the case of the development

Fig. 3. Rehabilitation of the lower limbs. The user's physical movement is shown on the left. On the right is a virtual scene that the patient sees when moving in virtual reality. The scene shows a wooden church in Hrabova Roztoka. (Source: own research)

of the musculoskeletal system of the lower limbs, it is necessary to focus equally on both limbs (affected and unaffected), as both are important in ensuring the stability and movement of the patient.

The rehabilitation program for stroke patients must be designed to address all neurological disorders that are expressed in the patient as a result of the disease.

The following criteria are important when drawing up a rehabilitation plan:

- assessment of muscle tone
- assessment of stage of stroke (acute, subacute, chronic stage)
- inclusion of appropriate rehabilitation methods.

For virtual reality rehabilitation, it was necessary to focus on developing individual scenarios that addressed patients with lower limb mobility, upper limb mobility and fine limb motor skills. For the needs of therapy, we created a series of virtual environments with photorealistic quality. Digital environment of selected cultural places (mansions, castles, temples, etc.), which positively influence the perception of patients (Lacko, 2017), or environments that are interesting in terms of interaction with 3D models of objects (especially indoor scenes with creation of objects, respectively manipulation with them). The created virtual environments were extended to include surround sound. The sound helped patients in terms of space orientation and identification of instructions for realization of rehabilitation tasks in the given environment. In terms of interaction, various scenarios were created in the virtual environment to rehabilitate individual parts of the patient's body.

The following scenarios were proposed for the needs of rehabilitation in virtual reality:

1. Scenarios for rehabilitation of the lower limbs

The patient moved in individual scenarios in the virtual environment on a flat area in the space of 3x3 meters so that his movement in the real environment and virtual environment was realized in the ratio of 1:1. We ruled out the need for teleportation to a location outside the confined space. In a virtual environment, the area was fitted with 3D models of paving, low or tall grass, so that the height of the patient's feet can be evaluated when the virtual obstacle is "exceeded". The task of the patient was to move in the space based on the therapist's instructions and "collect" virtual objects. The patient's position was evaluated by the head mounted display position in the space and by the position of the controllers. Hardware controllers were represented in virtual space as their 3D models, respectively. In some scenarios they were represented as virtual hands using rigged 3D models. The position of the lower limbs using external sensors was not determined in the scenarios. We used a treadmill to move patients over longer distances in a virtual environment, whose speed of movement was controlled directly by the patient. Thanks to the script-controlled position of the camera in the virtual space, we were able to measure the distance travelled by the patient during rehabilitation.

2. Scenarios for the rehabilitation of the upper limbs

The patient moved, stood on site, or sat based on the type of scenario chosen. The aim of the individual scenarios was to collect objects that were located statically in the space or to change their position dynamically so that the patient was forced to reach them by the affected limb. The limb position was represented by the position of the controller in the space, where orientation and position were evaluated as the position of the end effector. Based on the intersection of the position of the controller with the virtual 3D model of the object the success was evaluated. Another test case was to determine the position of objects in space by pointing a virtual cursor in a form of straight line from the controller position. The rate of response and the ability of the patient to mark the selected object with a pointer were evaluated. The pointer was shown only for the control located in the affected limb of the patient as shown in Figure 1. The last type of scenario was mirroring the position of the limbs. The patient was forced to move both limbs to the chosen position shown in the scene. We measured the deviation between their positions and the time the patient needed to reach the limb position.

3. *Scenarios for rehabilitation of fine motor skills of upper limbs*

In rehabilitation of fine motorics of the affected limb, we considered the degree of disability. If the patient was able to manipulate the controller, the hand gestures recorded were interpreted by pressing the buttons (trigger, grip ...). The gestures were transferred to the virtual 3D model of the patient's hand, and the interaction in the scene with the objects was realized as an interaction between the virtual 3D models. Another scenario was to use the tracking of the position and orientation of the user's hands without the need for a physical controller. The movement of the hands was monitored by a device that recognizes the position of the hands in space (watching a stereoscopic image in the infrared spectrum). The system plots their position by using a virtual skeleton of hands (as shown in Figure 2) from which the individual movements and gestures are transferred to a rigged 3D hand model. The interaction in the scene with individual 3D models is realized as in the first example.

For each scenario, we selected two patients (a total of six patients) who met the criteria for its completion, so that it is possible

a) to monitor changes in health status and use them to design final scenarios for test groups,
b) to measure quantitative parameters to create objective comparative mathematical metrics,
c) to design of artificial intelligence methods for monitoring the development and functional improvement of the movement of individual patients.

For the needs of virtual reality applications, we used the outside-in tracking method with HTC Vive (Vive.com, 2020) and Oculus Rift (Oculus.com, 2020). We used controllers of individual devices to monitor the position of the hands of patients. For the rehabilitation of patients' fine motor skills, we also used the Leap Motion (Ultraleap.com, 2020) device. In terms of comprehensive care of the patient during rehabilitation, his overall movement during the day was measured by a digital pedometer with the possibility of measuring individual phases of the patient's daily regime. For the purpose of moving the patient in virtual reality over longer distances, we used a treadmill for some application scenarios from which we transferred the processing speed to virtual reality applications via the TreadTracker.

Monitored parameters and artificial intelligence

In the rehabilitation of patients, we can focus on measuring various quantitative or qualitative parameters. The method of their measurement is directly dependent on the type of sensor that is used (position sensor, time measurement, sensor orientation measurement), their location on the patient's body, respectively measurement outside-in for controllers and the position of the head mounted display and the needs for which the measured data are intended (distance, time, possibly kinesthetics devices for force measurement, etc.).

We measured the position of the controller placed in the patient's hands. Thanks to timestamp measurements, it was possible to measure the position of the upper limbs in the space. For individual exercises in virtual reality, it was possible to monitor the progress or regression of the patient while performing the task when measuring the same exercises during rehabilitation. When measuring time data, we monitored the duration to complete the assigned tasks. The time for individual tasks started from the moment of exceeding the required position of the patient, so that it was possible to eliminate possible downtimes when entering the task and to objectify the results. The average speed was determined as the ratio of the path (e.g. when moving on a treadmill) travelled to the time required to travel it. These measured parameters were included in the quantitative parameters. In contrast, the qualitative parameters gave us a more accurate idea of how to perform individual movements. The individual monitored quality parameters were a combination of time parameters, device position monitoring parameters and information about the device orientation. In the case of using a device for tracking the position of hands (Leap Motion sensor) individual angles were measured in individual joints on the user's hand. By evaluating them, we were able to monitor the accuracy of the task, evaluate the mirroring between the affected and unaffected limb, or monitor the patient's progress in terms of fine motor skills.

By evaluating individual parameters, it is possible to increase the complexity of individual scenarios that the patient implements within the rehabilitation. In individual scenarios, we can incorporate artificial intelligence methods into the rehabilitation process based on metrics obtained from the evaluated parameters. In our case, we measured the patient's progress in manipulating objects in virtual reality through the upper limbs. It turned out that the smaller objects were more difficult to handle by patients. Therefore, when monitoring the patient's progress during individual sessions, we evaluated his abilities from previous weeks of rehabilitation and based on the change in his health condition. Then we offered a given task with a variety

Tab. 2. Results of the patients with stroke after rehabilitation in virtual reality

Patient	Scenario	No. of apps in scenario	Controllers	No. of VR sessions/overall sessions	Measured parameters	Overall progress *
#1	Lower limbs	5	HMD controller, Treadmill	12/24	Walking distance, walking speed, walking accuracy, path tracking	27%
#2	Lower limbs	4	HMD controller, Treadmill	10/20	Walking distance, walking speed, walking accuracy, path tracking	19%
#3	Upper limbs	6	HMD controller	12/24	Movement tracking, movement accuracy, orientation of the limb, mirroring accuracy	43%
#4	Upper limbs	6	HMD controller	11/24	Movement tracking, movement accuracy, orientation of the limb, mirroring accuracy	29%
#5	Fine motor skills of upper limbs	3	HMD controller, Leap motion sensor	12/24	Angle accuracy, movement tracking, movement speed, movement accuracy	35%
#6	Fine motor skills of upper limbs	5 (combined with apps for upper limbs rehabilitation 3+2)	HMD controller, Leap motion sensor	12/24	Angle accuracy, movement tracking, movement speed, movement accuracy	26%

* Measured as weighted average of increasing of quantitative and qualitative parameters
(Source: own research)

of large objects (for better motor skills, the smaller objects).

Tele-rehabilitation and virtual reality

During the verification of our hypotheses, we were partially limited by the COVID-19 crisis, so it was not possible to carry out part of the rehabilitation in virtual reality in direct contact with the physiotherapist. For this reason, we decided to carry out part of the research through remote access using tele-rehabilitation methods. Patients were provided with a virtual reality kit for home use. The number and continuity of individual tasks were consulted through tele-rehabilitation. However, as it turned out, this method required some practice from the patient in the use of the device, and it was also possible to evaluate the fulfilment of the criteria only by subsequent analysis of the data sent.

RESULTS

Patients were tested for rehabilitation methods for 6 weeks, with a combined hybrid approach using traditional physiotherapeutic methods and virtual reality rehabilitation. Patients attended traditional rehabilitation once a week, and a 30-minute virtual reality session was held twice a week. During the day, patient activity was monitored by pedometer, pulse evaluation and sleep cycles. In addition to performing rehabilitation, patients practiced daily based on prescribed physical exercises focused on the affected part of the body. Rehabilitation results can be divided into quantitative and qualitative parameters. Quantitative parameters were related to measurable quantities, taking into account the rehabilitation parameters (number and time of exercise, number of classical and virtual rehabilitation, pulse change during exercise) and limb momentum change parameters measured in each virtual reality use scenario. Changes in momentum can be considered changes in terms of time of tasks and changes in terms of measurable indicators in space (angle of bending of individual joints, reach of limbs, number of steps, etc.). The monitored qualitative parameters were set subjectively and provided an overview of the change in the patient's quality of life. Within the qualitative parameters we also focused on the evaluation of the impact of virtual reality and virtual environment through the "WOW" effect on the patient's motivation to rehabilitate and perform the assigned tasks. In addition to these variables, we also gathered information on the impact of multisensory perceptions from a positive rehabilitation environment on patient satisfaction and the motivation to perform increased rehabilitation performance. The results for the patients under review are summarized in Table 2, which shows that all patients had an improvement in their motor skills.

After processing the results, patients using the combined hybrid form of post-stroke rehabilitation showed to be more motivated in terms of access to exercise, as virtual reality provides them with an alternative to conventional exercise with physiotherapists. The form of serious games is interesting for patients in terms of the way of interaction, the possibility of individualization of rehabilitation techniques and finally in terms of immersion and perception of a positive and motivating photorealistic virtual environment. According to patients, there are limiting factors resulting from the lack of experience in the use of virtual reality, especially in the elderly, but which are balanced by the "WOW" effect. This effect disappears over time during individual rehabilitation, as the patients are accustomed to the influence of the virtual environment on their perception, but at the same time the ability to interact in the virtual environment is improved through the user's controllers or gestures.

Based on the established hypotheses, it was possible to draw the following conclusions on selected patients:

- H1: Rehabilitation through virtual reality can contribute to a more effective process of rehabilitation of patients after stroke.

The use of virtual reality in rehabilitation in combination with standard procedures brings several advantages in terms of increasing the motivation of patients to perform individual exercises. Thanks to the "WOW" effect, the patient is better aware of the progress he is making during exercise, and exercise in virtual reality can be perceived as a game in which motor skills are improved based on the patient's subconscious work with his limbs.

- H2: The measurement of quantitative parameters and their evaluation can contribute to the creation of more effective methods of tele-rehabilitation.

The ability to measure individual parameters to a specified degree of accuracy can lead to the creation of personalized scenarios, monitoring the progress or regression of the patient. In the case of regression, it is possible to return to the previous settings of individual parameters on the basis of decision functions or on the basis of the involvement of artificial intelligence methods. Individual measured quantitative and qualitative parameters can be used in tele-rehabilitation. Thanks to their evaluation, it is not necessary to monitor the patient remotely only through video and control his procedures visually, but it is possible to see and evaluate individual monitored data in real time.

Based on our testing of patients after stroke using virtual reality, progress was confirmed in all monitored cases and scenarios, which will need to be verified in a subsequent comparative study. Patients showed signs of significant improvement in motor function, which we also had supported by the outputs from the measured data. In addition, patients who received therapy were monitored in a comprehensive approach through a tracking bracelet, which recorded the patient's activity outside of classical physiotherapy and rehabilitation in virtual reality, thanks to which we obtained information about the daily rhythm of patients and could set individual scenarios within the exercise accordingly.

DISCUSSION

Based on the results, the impact of individual parameters on the overall success of the hybrid approach to rehabilitation was evaluated. It appears that the use of virtual reality in the process of rehabilitation has a particularly motivating characteristic for the patient. The created virtual environment and focusing on the fulfilment of serious games instructions has a direct impact on the quality of execution of individual rehabilitation exercises. As the patients point out, in respect to the created environment they prefer the photo realistically processed 3D scene in which it is possible to navigate comfortably in space and concentrate directly on the performed activity. As part of the results, we focused on measuring patient performance through a basic set of controllers that are part of the head mounted displays. The position and orientation of the user's head and hands determines the position and number of steps that the patient should have taken in the scenario. For the purposes of further analysis, we plan to deploy other types of sensors to measure the position of the knee joints and ankles in the space and measure the quality of the patient's stride. This approach has proved to be important for evaluating the patient's movement patterns and designing individual rehabilitation procedures.

During testing of rehabilitation methods, we found out that it is not appropriate to use unified procedures and created environment for all users. Personalization of procedures, including environment personalization, plays a major role. If the users have a choice of different environments, they can choose the one that evokes positive feelings for them and is used to perform individual rehabilitation exercises. From a psychological point of view, rehabilitation involves the creation of an emotionally positive approach that breaks down barriers to practicing individual activities. The question is whether the same feelings in the patient and increased motivation would occur in the use of rehabilitation procedures in the form of serious games, even if virtual reality means are not used. We also realized this possibility during testing. It appears that patients perceived the use of virtual reality more positively (as long as the conditions for their use were met), which was justified by a better sense of immersion in the environment and subjective interaction with the environment, even though the interaction was done in the same way (2D on the monitor and stereoscopic display using head mounted display). Using virtual reality, patient instructions were implemented through a physically present physiotherapist who had the opportunity to adjust the rehabilitation scenario based on individual patient outcomes, or to control the number of repetitions of each activity. In the case of involvement of artificial intelligence methods in the process of evaluation of activities, it is possible to implement individual procedures even without the presence of a physiotherapist e.g. in the patient's home environment. An alternative to the use of artificial intelligence is the possibility of realizing tele-rehabilitation using remote access. However, the patients evaluated the possibility of direct contact with the physiotherapist as a good part of therapy also in terms of communication. On the other hand, however, such contact can cause the patient to concentrate on the activity being performed and/or to disrupt the patient. Reduce the impact of ambient sound in the patient's auditory perceptions to complete the individual scenarios. Sound contact with a physiotherapist can be replaced by instructions based on speech synthesis processed by artificial intelligence procedures.

In the selection of patients, we worked with walking patients who were oriented in space and had the ability to at least partially involve hands in the implementation of activities due to interaction. Hybrid rehabilitation could also be used for recumbent patients after system modifications. The use of weightless simulation is an interesting option for these patients. During its simulation, the necessity of movement in space through walking is abstracted. As a negative, we can see the possible loss of orientation when moving in all directions (we used the simulation of the weightless state when moving through the space station for testing).

To simulate individual virtual reality activities, patients had to manipulate 3D object models. In the case of manipulation by controllers, the haptic perception was ensured directly by holding a physical controller, or we simulated the object grabbing by the controller's vibration. When using the Leap Motion system, where the user used only their hands, it was not possible to perform a haptic simulation and the users lacked a haptic response. This problem could be solved by involving a combination of physical objects tracked in space and displaying them in virtual space through their 3D models. For this approach, however, it is necessary to add another element to the system, the motion capture system, which can make the entire virtual reality system more expensive.

CONCLUSION

The results presented in our research were comprehensively focused on the possibilities of using virtual reality in the treatment of selected patients after stroke, the possibility of data acquisition and comparison. In individual patients, in addition to the influence of digital technologies on the improvement of limb mobility, we also monitored the development of their quality of life from a psychological point of view. The presented results will be verified in a comparative study, showing that in future work we will focus on creating personalized environments with the possibility of digital cooperation between patient and physiotherapist in a combination of virtual and augmented reality, using artificial intelligence methods to evaluate progress and use intelligent chatbots in synthesis of patients' speech and the possibility of deploying virtual reality for horizontal patients.

DECLARATIONS

Ethics and consent to participate statement

This study was approved by the Ethics Committee of Pan-European University in Bratislava, Slovakia. Written informed consent was obtained from the patient for publication of this research.

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