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VIRTUAL REALITY POSTSTROKE REHABILITATION WITH LOCALIZATION ALGORITHM ENHANCEMENT

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ABSTRACT The work presents an analysis of the application of virtual reality technology in rehabilitation after the occurrence of stroke. The needs in poststroke therapy, as well as the requirements and technological possibilities were investigated, with the result being the creation of the application for post-stroke rehabilitation. Tests on the application, as well as analyzed studies have shown that this way of rehabilitation as an isolated therapy is not enough to improve the condition of patients. The combination of rehabilitation in a virtual and conventional manner provides a positive effect on the improvement of medical patient motor functions based on the surveyed patients.

Keywords: virtual reality, poststroke rehabilitation, stroke therapy, 3D localization, Time-of-Flight, localization algorithms

1. INTRODUCTION

Virtual reality technology enables one to experience the virtualized world in digital space. It introduces the immersion effect, providing a real experience of being in a different reality. This includes visualization, sound, touch and interaction with objects in a virtualized system, along with hardware that enables users to connect to the virtual space.

There are many commercial systems available that connect the user to the virtual world and enable interaction. This technology has great potential and is used in many consumer-focused applications, mostly in entertainment as a medium for games, simulations or filmography. Another branch is the development towards its use in medicine. Simulators of treatment are being developed, as well as for exercises and rehabilitation. It has been noted that some commercial projects are able to provide the appropriate amount of movement to support rehabilitation therapies.

The creation of dedicated systems for this purpose include the works of Da Gama and Weiss. (Da Gama et al. 2015, Weiss et al. 2006), in addition to conventional therapy being transferred to the virtual world (Dias et al. 2019, Covarrubias et al. 2015). This solution was beneficial for people after stroke, as their attention could be focused only on the task, and not on the inhibiting factors to exercise, such as pain or lack of motivation, with all this due to immersion. When the experience is engaging, one can forget about troublesome ailments and use virtual reality as an alternative way of poststroke rehabilitation.

2. METHODS AND MATERIALS

2.1. Literature Review

2.1.1 Rehabilitation System for Stroke Patients

The work by Cho et al. (2014) examines the design of a Virtual Reality (VR) proprioception platform designed specifically for patients who suffer from strokes. People with shielded hands move their hand to the target depicted as:

- A transparent cylinder moved with one hand;
- A colored cylinder being the target.

The patient considers the afflicted position of the hand to correspond to the target, the hand that is unaffected presses the button. The distance between the target and hand is measured.

The work presents simple correlations before and after testing with the proprietary system. The results are based on conventional post-workout behavioral tests, though it is shown that efficacy and adoption of VR to regain proprioception of patients suffering from stroke has potential. The noteworthy aspects of the implementation include:

- VR environment utilizing magnetic-based hand movement sensors;
- Employing proprioception in the VR platform, the sense of orientation of the body part being tested;
- Testing of hand function using Jebsen-Taylor approach; and
- ANOVA and T-testing were used to compare training effects.

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2.1.2 Patient Platform for Cognitive Rehabilitation

Covarrubias et al. (2015) has developed a system of moving objects in VR, that generates aromas such as chocolate, rose and orange essences. The rehabilitated person should move these objects according to the instructions, and the scent should generate adequate concentration for the user to identify.

These studies were partly developed from the Tele-Rehabilitation Ability project. This integrated platform enables remote control and delivery of cognitive and physical rehabilitation, as well as independent management. The equipment used for the experimental platform includes:

- Monitor utilized to display and render virtualized environment;
- Oculus Rift headset adopted to display a virtualized environment stereoscopically;
- Leap motion controller tracks user hand movements and gesture detection in free space;
- Multi-Fragrance Olfactory Display (MFOD) delivers odorous compounds;
- Arduino embedded microcontroller board controls the MFOD component in a logical manner.

2.1.3 Patient Platform for Cognitive Rehabilitation

Laver et al. (2018) provides a comprehensive review of VR in stroke rehabilitation, confirming that VR is readily acceptable for physiotherapy rehabilitation purposes. The work considered 72 samples, in which 2470 participants in total took part. The review factors 35 supplementary studies, as well as the studies included in previous reviews. The size of the research trials was generally small in nature, and the interventions differed in both the goals of the treatment and the VR devices being used for experimentation.

2.1.4 Reinforced-Feedback Rehabilitation Platform

Kiper et al. (2011) discusses a rehabilitation application in VR, which was controlled by the hand using gloves with receivers. The application image was displayed on a digital projector. The methods used in the platform include:

- TNR: Traditional Neuromotor Rehabilitation; and
- RFVE: Reinforced Feedback in Virtual Environment.

The use of RFVE, combined with the principles of TNR lead to more improvement than treatment with only TNR. Therapy in a virtualized environment included with TNR was inherently effective by twice as much compared to intensive TNR in patients, after ischemic as well as hemorrhagic stroke. The improvement after RFVE concerned not only patients after ischemic, but as well as hemorrhagic stroke conditions.

2.2. Rehabilitation Approaches in Virtual Reality

The main guidelines used in the virtual reality of stroke rehabilitation are based on neurobiological principles. The learning of new strategies and movement patterns are dependent on them. Improving motor skills are achieved by using the brain's ability to learn and adapt with increasing intensity of motor tasks, with the motor regeneration principles as follows (Ovbiagele and Turan 2015, Laver et al. 2018):

- Brain plasticity,
- Mirror neuron systems, and
- Brain reward system.

This is made possible by the plasticity of the brain, which is influenced by the reorganization of the cerebral cortex and changes in the damaged brain (Kiper et al. 2011). Intensive training and the observation, practice and representation of task-related activities on the screen can facilitate the reorganization of the cerebral cortex. This is also influenced by the involvement of mirror neuronal systems. Learning by imitation can lead to activity-dependency organizational concerns with the motor-neural cortex via mirrored neural networks. Participants receiving sensory feedback throughout training in virtual reality systems learned the motor pattern through imitation (Jang et al. 2005), with the so-called brain reward system used, thus increasing the motivation of the patients.

This system is a group of mesolimbic pathways mediated by dopamine. They are activated while the patient experiences the influence of video games. Virtual reality applications use appropriate concepts in stroke rehabilitation including frequent repetition, high intensity and tasks aimed at training paresis limbs (Cho et al. 2014), ranging from non-immersive to fully engaging activities. They also provide clinicians with the ability to control and evaluate tasks, with programs often including multimodal, real-time feedback (Weiss et al. 2006), as one can test tasks and dangerous situations in practice being designed to be used unattended. This allows one to increase the dose of therapy without increasing external labor and to conduct rehabilitation treatments at home, without loss in the quality of rehabilitation.

It is noted to assess the effectiveness of VR technology in its aims to give direction to the design and use. Much research is still being done, with the abovementioned studies already carried out showing positive results, and this area is developing rapidly in pace and scope.

2.3. Effectiveness of the Platform

To check the effectiveness of the hitherto applied poststroke rehabilitation with the use of VR, the latest available studies have been researched. There were materials used between the years of 2015 to 2018. The results in the analyzed group of studies are relatively similar. A 2015 study by Cochrane (Laver et al. 2015) found that adopting VR and interactive-based video games can be advantageous in optimizing upper limb functionality and restoring daily activity. This is possible when applied as a supplement to normal care or when considering the similar dose of conventional-based therapy. Current work has not been confirmed whether the effects obtained will persist in the long term, with further evidence required to draw conclusions about the impact on:

- Gripping power,
- Walking speed, or
- Global motor functions.

In 2017, the research work was extended with additional data (Laver et al. 2017). The results for upper limb function were not statistically significant when comparing virtual reality with conventional therapy. However, utilizing VR in combination to normal care it provided a greater dose of therapy, so there was a significant level of improvement statistically. It was found that this alternative method could be advantageous in assisting upper limb ability and regular life functions when complementing normal care. The most recent diagnosis has also shown that conventional therapy is more effective than isolated rehabilitation in virtual reality. The review showed that the following rehabilitation factors did not significantly affect the outcome (Laver et al. 2018):

- The effective dependence of time on stroke occurrence,
- Extent or severity of medical handicap of the patient, and
- Type of VR hardware device.

By using virtual reality to complement normal care, as well as raising the number of participants in the work, it showed statistically significant differences to groups using only one type of treatment. It was also noted that personalization of rehabilitation programs in virtual reality was better than commercial games, but the results were not statistically significant. It should also be noted that the size of study samples was mostly small, the virtual reality devices used differed from each other, as well as the purposes of treatment of the conducted analyses. Further studies are being carried out, in addition to virtual reality technology still being developed. It now can be observed that it brings significant results in combination with conventional care. However, more targeted research on a larger scale is needed.

2.4. Application for Poststroke Rehabilitation

The main objective of the project was to create an application in a virtual environment, which can be used as an aid in poststroke rehabilitation in the field of performing precise movements of upper limbs and recognizing and identifying objects. The application includes exercises in conventional physiotherapy, which are to be performed based on reaching the next levels in the game and scoring greater points. The tasks performed having different levels of difficulty. For the newly designed VR application to be useful to the patient and medical clinician, the rules for user immersion and the sense of presence in the game had to be applied. The object manipulation tasks include:

- ***Articulation:***
  Reaching out to ultimately grab the virtual object by means of articulation, by the extension of the patient's hand towards the object they want to manipulate,
- ***Grasping:***
  Acquiring the target by squeezing the object to determine its plasticity or sponginess, to determine the ability of the patient to grip the object for further exercises by a medical specialist or clinician, and
- ***Manipulation:***
  Moving the object to place the object from one region of space to another, to determine the level of precision or accuracy that the patient can conduct the specific task or exercise for assessment by a third party.

After creating the application, it was possible to test it on people after a stroke, with experiments conducted at the Department of Neurological Rehabilitation, Regional Specialized Hospital in Wrocław, with rehabilitation using virtual reality applied at the facility for the first time with patient consent.

The medical center provides care and rehabilitation for patients with cancer, inflammatory consequences of central nervous system diseases, multiple sclerosis and systemic primary atrophies occupying the central nervous system, as well as after stroke care. This work will continue to build upon the previous research done in the hospice, and that we will continue to collect and refine test data on a larger group of patients.

3. CURRENT PLATFORM RESULTS

3.1. Current Technology Framework

The created platform uses Oculus Rift. It is a tool that enables to connect the user with virtual reality. It meets all the conditions to ensure that the immersion is maintained. The Oculus Rift consists of goggles and two sensors. Moreover, the Leap Motion controller is used. It is a device capable of tracking all ten fingers of a hand. It provides gesture tracking for control in a virtual reality environment. In conjunction with Oculus Rift, it reproduces the position and actions taken by the user to the computer system. The following software was used to create the application:

1. *Unity 2018.1.6:* A multi-platform game engine, which is the necessary programming tools selected for the project. Oculus SDK, which is attached to the applied Unity version and additionally the Leap Motion SDK.

2. *MonoDevelop:* Integrated open-source programming environment used to create C# scripts.
3. *Blender:* 3D software for creating computer graphics.

The platform uses the Oculus headset, that is connected to a laptop computer with an Intel Core i7 processor, a GeForce graphics processing unit and 16 gigabytes of main memory. The computer runs the Microsoft Windows 10 Professional operating system, with additional software development toolkits installed including the Leap Motion and Oculus device libraries to interface the hardware with the software subsystem.

3.2. Rehabilitation Exercise Platform

Three patients approached the preliminary studies of the application. The patients were in a similar condition. All had efficient upper limbs, however there were various degrees of problems with loosening and grabbing one of the hands. Patients performed three rehabilitation tasks shown in Figure 1 on the following page.

The first patient started the test with a positive attitude. It took him a while to get acquainted with the new technology. No major difficulties were encountered while performing the tasks. During some tests he was able to spread his hand completely and release the ball. In the case of unsuccessful grabbing, he picked up the ball from the bottom and moved it to the designated place. All three tasks were completed.

The second patient had some skepticism and was scared, but after getting acquainted with the equipment the fears were dealt with. The patient had more difficulty in using the right hand and put more effort into completing the tasks. In case of a failure to catch the ball, he compensated for the force and instead of grabbing it with his hand, he 'threw' it which made it easier to carry out the command. The biggest problems occurred during the third exercise. Small breaks were needed between activities. The help of the physiotherapist in mobilizing the patient was important. The patient was able to complete all the tasks, after which he showed enthusiasm for the completed training. As the exercises progressed, opening the hands to move the ball became more efficient.

In the third attempt, the patient showed no prejudice. He willingly went on to tasks that did not cause him any major problems. He did not always manage to open his paresis hand, but many attempts made it easier. Here too, the activity of grabbing the ball from below was used, making it easier for him to complete all his exercises.

The opinions expressed by the test patients were favorable, as they considered it an interesting experience and expressed their willingness to use the application in everyday rehabilitation, although sometimes it required concentration and reflection on their part. The usability of the system was an important focus in the system design, such that patient needs were considered throughout the experimental task. Because of observing patients during the exercises, it was possible to draw conclusions that could not be deduced easily in the computer laboratory.

The experimental work was enhanced through practical on-field assessment of patients and their interaction with the rehabilitation platform in the following manner:

- ***Mode of Operation:***
  Grabbing of the ball in a clenching motion in by the medical patient within the virtual rehabilitation platform.
  - The way the virtual balls are grabbed is essential, as it is important to clench the hand and move the ball in the virtual space.
  - In many test cases, the ball was picked up from the bottom without much or minimal hand work from the current set of test patients.
  - This indicates that familiarity with the system was accomplished with recurring usage.
- ***External Intervention:***
  Actions required to ensure the medical patient is comfortable with the use of the virtual rehabilitation platform.
  - Accomplished by means of changing the patient's attitude and calming them down as necessary.
  - It is possible that initial hesitation and uncertainty over the technology was caused by the first experience with the application.
  - Assumptions cannot be made into the patient's prior experience with VR systems.
  - Incremental improvement over the user interface design is essential to help overcome technological barriers with the test patients.

Repeated attempts would eventually eliminate this problem through familiarity of the virtual environment, as well as positive encouragement with the patient as they engage with the rehabilitation platform. However, the intervention of the rehabilitator assists in the initial use of the experimental system, such as to train up the patient to be familiar and ultimately be at ease with VR technologies.

4. MAIN REHABILITATION OUTCOMES

The next step is to evaluate the effectiveness of the experimental application on a small test group. As observed in the Functional Classification of Handling Grip scores elaborated in Table 1 (Enjalbert, Pelissier and Blind 1998, Pélissier, Benaïm and Enjalbert 2002), connecting the handling gripping parameters to existing research would enhance platform usability into human mobility.

Thus, this allows for a thorough comparison and contrast between VR and physical testing approaches.

The testing classification approach will be consulted with medical professionals in conjunction with Wrocław Medical University to determine the optimum assessment approach. There are many other methods for measuring effectiveness of poststroke rehabilitation (Scrutinio et al. 2019, Turner-Stokes 2010). We decided to apply the mentioned system as shown in Table 1.

After the rehabilitation exercises, each patient got an appropriate mark shown at Table 1. Obtained results are present at Table 2. Mark in the column 'Start' describes initial state of patient and in the column 'End' final state. A small improvement after the test is observed. In our opinion, the optioned results seem to be promising. We expect more results during the next session of rehabilitation exercises.

Table 1: Functional classification of handling grip (Enjalbert et al. 1998, 2002)

Note: Test Only Valid in Vascular Hemiplegics

Level	Test Description
0	• No recovery in grasp; • Zero gripping ability.
1	• Syncinetic reflex approach in abduction-shoulder retropulsion; • Includes elbow bending.
2	• Analytical approach without possible grasp.
3	• Analytical approach with global grasp; • Without actively releasing grasp or letting go.
4	• Analytical approach with global grasp; • Actively releasing grasp or letting go.
5	• Existence or the ability of a tri-fingered grasp.
6	• Gripping normally with fine clamp of the object.

Table 2: Observed results of poststroke rehabilitation

Patient	Start	End
1.	4	4
2.	3	4
3.	3	4

A new series of tests for a larger group of patients will be carried out in August. The results will be presented at the VARE September 2019 conference session in Lisbon.

5. FURTHER WORK

5.1. Application Development Approach

In this research, the application will be used to study the position of hands in space, with the consideration made into applicable localization algorithms useful for medical diagnosis purposes (Olech 2018). It will employ extensive use of the Leap Motion controller, a device that tracks hands across a wide range of lighting and environmental conditions. The software is developed in C++ and utilizes the Qt library.

Integration of the coordination data with the existing platform can be accomplished using readily available Application Programming Interfaces (API) included with the controller hardware. The application displays various tracking data provided by the Leap Motion Application API for three axes of positional coordinates in time.

In this manner, it verifies if the hand position at a given time has not exceeded the admissible range for a healthy person. For each rehabilitation task, a new session is created in the application and recording the hand position during the task. The collected data is displayed on visual charts and will be exportable for further analysis by medical experts. The length and path of the hand movements are to be recognized in a logical manner, such that the smoothness of the path can be properly evaluated by the clinician in real-time.

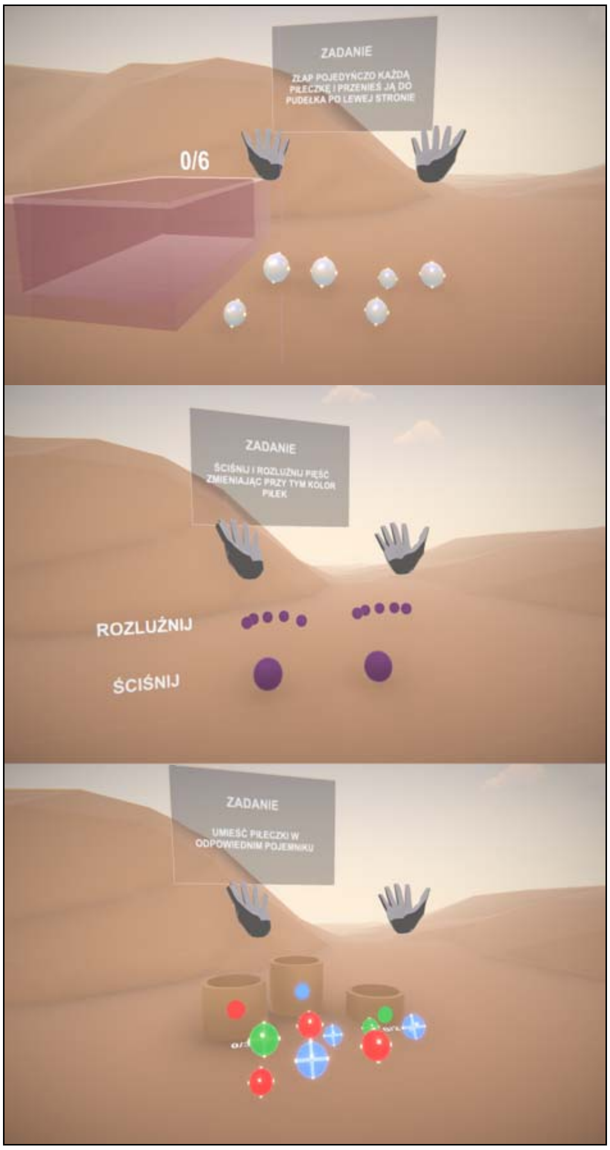

Figure 1: Experimental rehabilitation application scenes demonstrating coordination testing system; with the scoring based on the number of balls successfully placed in a generic bin (*top*), digit coordination (*middle*) and color-coded bins (*bottom*) (Marzec 2018)

The fine motor coordination skills of the patient will be determined by the amount of oscillation observed during the path of the hand, and eventually compared against a database of anonymized patients with healthy hand movements of a similar age range. In this way, a comprehensive process can be established for diagnosing patients in a structured manner, that aims to minimize potential subjective bias in the testing program that can occur with manual assessment.

The next step is to evaluate the effectiveness of the experimental application on a larger test group to improve the platform. As observed in the Functional Classification of Handling Grip scores elaborated in Table 1 (Enjalbert, Pelissier and Blind 1998, Pélissier, Benaïm and Enjalbert 2002), connecting the handling gripping parameters to existing research would enhance platform usability into human mobility.

Thus, this allows for a thorough comparison and contrast between VR and physical testing approaches. The testing classification approach will be consulted with medical professionals in conjunction with Wrocław Medical University to determine the optimum assessment approach.

5.2. Research Scope of Platform

Currently, rehabilitation in a virtual environment is not enough as an isolated therapy, as test patients require physical exercise and training for a more holistic experience. This is the result of extensive research being carried out on existing VR rehabilitation systems, as well as the testing of the created application for patients at the Department of Neurological Rehabilitation, Regional Specialized Hospital in Wrocław.

The initial responses from the test patients show that further work into the platform is warranted, along with additional enhancements into the interaction experience to improve user immersion.

Therefore, this is expected to optimize the familiarity of exercises performed in the virtual environment in the following manner:

- ***Patient Survey:***
  Their personal opinions will be considered as part of the application design phase, for technical refinement and quality assurance purposes.
- ***Continuous Feedback:***
  Assessing the regular feedback of users is part of the iterative design principles, as well as make incremental changes into the experimental platform after all relevant stakeholders are factored into the rehabilitation process.
- ***User Centric Design:***
  In this way, we seek to integrate usability concerns, which is an important qualitative issue typically overlooked in system design.

The application in the virtual environment was positively received by patients and physicians. Its immersive action encouraged the users to participate in rehabilitative exercises and seek out additional remediation therapies as necessary. The technology was an initial barrier, as with any reticence for new platforms, that was overcome through familiarity and engagement with VR technologies and their associated use cases. Such a concern will take time to overcome, but current work shows initial promise.

As the current experimental work deals with an effective VR training process, it builds upon on the important physiotherapy work of Kiper et al, 2011 and Laver et al. 2015, 2017 and 2018. It is important to note the current work is expandable to a larger patient test base – thus accommodating a wider variation in demographics and physical capabilities of medical patients.

Even though the current method itself shows promise, putting on the VR equipment did present fear and anxiety in some patients. Thus, the current work needs to continue focusing on the most notable limitations when designing such rehabilitation and training programs. Furthermore, VR is still not widely used in the rehabilitation of people after stroke in centers where this type of rehabilitation is carried out, so it presents new opportunities for human development and technical evaluation.

6. CONCLUSION

The research work examines the efficacy of the rehabilitation platform after a certain period of use. The influence on motor coordination functions was not satisfactory in comparison with normal therapy in isolation, although experimental factors including small test patient samples and technology limitations could affect the eventual rehabilitation outcome of the patient given research into this medical domain.

In combination with virtual and conventional rehabilitation, the effect on motor function was better than with normal therapy (Kiper et al. 2011), as well as the analytical diagnosis data generated from the VR exercises. This data was forwarded to physiotherapists for further analysis and examination. Comparing the results with conventional rehabilitation is key to assess the advantages of this newly designed approach into medical healthcare.

Along with building a database of healthy hand movements for rehabilitation assessment, this will assist in the analytical process – such as to provide a greater longitudinal study into this field of research. Rehabilitation tasks can be diversified by focusing on the creation of personalized exercises adjusted to the patient and their needs, tailoring physiotherapy techniques as necessary.

The cooperation with the Department of Neurological Rehabilitation, Regional Specialized Hospital in Wrocław along with Wrocław Medical University will continue as current results have proven fruitful, with further contact and engagement with patients and doctors being essential to effectively construct an authentic rehabilitation medium.

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