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Master Thesis

Computer-aided rehabilitation system in patients after a stroke

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keywords:
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hand tracking

short summary:

The work focuses on the proper application of virtual reality in rehabilitation after a stroke. An application created in the engineer's thesis was developed and a tool to assess the progress of the rehabilitation process by tracking the position of the hands. The developed software has been evaluated on five testers. The obtained results are satisfactory. Ultimately, the system obtained is a good basis for further steps to introduce it to the common use.

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Streszczenie

Praca skupia się na właściwym zastosowaniu wirtualnej rzeczywistości w rehabilitacji po udarze mózgu. Na podstawie przeprowadzonych badań dotyczących aspektów bezpiecznego i immersyjnego środowiska wirtualnego rozwinięto aplikację stworzoną w pracy inżynierskiej. W celu zwiększenia użyteczności systemu stworzono narzędzie do oceny postępów w procesie rehabilitacji, polegające na śledzeniu położenia dłoni i opierające się na rozwiązaniach stosowanych obecnie. Oprogramowanie zostało przetestowane na pięciu testerach. Sprawdzono jak w praktyce działa autorska metoda oceny rewalidacji oraz zbadano wpływ aplikacji VR na użytkowników. Do tego celu wykorzystano Simulator Sickness Questionnaire oraz Game User Experience Satisfaction Scale. Uzyskane wyniki są satysfakcjonujące. Aplikacja VR nie wpływa znacząco na chorobę symulatorową, a rozgrywka dzięki zastosowanym interakcjom jest wciągająca i przyjemna. Przeprowadzona analiza pozwoliła również określić, które części systemu powinny zostać zmienione lub rozwinięte. Wywnioskowano, że aby system rehabilitacyjny sprawdził się w codziennym użytku należy narzędzie służące do oceny ruchów zintegrować z aplikacją VR. Kolejnym ważnym czynnikiem, mogącym poprawić jakość rozwiniętego systemu jest wprowadzenie fabuły do rozgrywki, pozwalającej na większe zaangażowanie użytkownika. Ostatecznie uzyskany system jest dobrą bazą do dalszych działań w celu wprowadzenia go do powszechnego użytku.

Abstract

The work focuses on the proper implementation of virtual reality in rehabilitation after a stroke. On the basis of the conducted research concerning aspects of safe and immersive virtual environment, an application created in the engineer's thesis was developed. In order to increase the usefulness of the system, a tool to assess the progress in the rehabilitation process was created, based on the hands position tracking and solutions used nowadays. The developed software has been evaluated on five testers. The proposed method for assessment of revalidation was tested in practice and the impact of VR application on users was examined. Simulator Sickness Questionnaire and Game User Experience Satisfaction Scale were used for this purpose. The obtained results are satisfactory. The VR application does not significantly affect cybersickness, and the gameplay thanks to the applied interactions is engaging and pleasant. The analysis also allowed to determine which parts of the system should be changed or developed. It was concluded that in order for the rehabilitation system to work well in everyday use, the tool for evaluation of movements should be integrated with the VR application. Another important factor that can improve the quality of the developed system is the introduction of the storyline to the game, allowing for greater user involvement. Ultimately, the system obtained is a good basis for further steps to introduce it to the common use.

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Chapter 1

Introduction

Virtual Reality (VR) has become a popular medium. The devices used to connect the user to the Virtual Environment (VE) are developing very quickly, reacting to problems and user feedback. In 2015 the first consumer version of the headset for virtual reality, Gear VR, was released from Samsung. Since then, these devices have been continuously improved. Also, the applications designed to work in virtual reality are changing. In addition to viewing the world in a Virtual Environment, it is also possible to interact with it and gain feedback that can bring the user into a state of immersion. VR applications range from games and movies to simulators and tools for therapy and training.

The effectiveness of created solutions in virtual reality technology is being examined. Currently, there is no system allowing for VR rehabilitation that could be commonly used in rehabilitation centres or at home. Attempts are being made to create exercise solutions for people affected by various diseases. However, these are prototype models which are being tested and improved. The results of such measures cannot be clearly determined due to the variety of applied exercises and the often unrepresentative test sample [1].

In an earlier study [2], research on rehabilitation after a stroke was realized. The types of existing therapies, guidelines to maintain during rehabilitation and exercises applied to make physiotherapy effective were examined. The gathered information was used to create a virtual reality application for Oculus Rift and Leap Motion. It allows to perform basic exercises used in conventional therapy. It was verified if this method of revalidation is effective. The application was tested on three patients after a stroke. Their first approach, acceptance of the application and willingness to use it in everyday exercises showed the validity of developing a new method of poststroke rehabilitation. It may diversify existing practices and, more importantly, shorten the time of returning patients to physical abilities.

1.1 Aim and scope of work

The aim of this work is to build a system for the poststroke rehabilitation of upper limbs and to examine its usefulness. The system includes an application in virtual reality technology and an application recording the position of the hand. The VR application will be developed from the version presented in the engineer's thesis [2] in order to better adapt it to the needs of users. For this purpose, the properties of a safe virtual environment conducive to immersion will be analysed. During the development, issues from previous research will also be taken into account. This is mainly focused on increasing patient motivation during exercises and creating an easy-to-use interface. The next phase is to

examine the existing methods used to evaluate the progress in the rehabilitation of the upper limbs and to propose solution using the recording of hands movements. Finally, the created system will be tested.

Chapter 2

Virtual Reality Experience

2.1 Virtual environment

A Virtual Environment (VE) is provided by Head-Mounted Displays (HMD). VE simulates worlds that can involve users in contextually relevant actions and that can generate various user experiences (UX) depending on the chosen environment. Proper mapping of body motions and game events and appropriate feedback of the system will generate a realistic environment that is important for the user's sense of presence.

2.2 Immersion

The main aspect that indicates the effectiveness of VR technology is immersion. Immersion refers to the sensual faithfulness of the virtual environment. How extensive, surrounding and matched it is [3]. There are three levels of presence in the game [4].

- **Engagement**

This is the first entrance level. It occurs before every other level. It is influenced by steering and feedback. The user must be aware of the system of movement in the game, controlling the main functions of the game immediately after the start. Feedback and interactions should be appropriate to the tasks and encourage the player to spend their time in the game. They are required to compensate for the player's efforts. The ability of the system to engage is an indicator of good gameplay.

- **Engrossment**

From the moment of engagement, the user is able to get more involved with the game. The barrier here is the structure of the game. It is overcome by visualizations, tasks and plot. By providing absorbing experience, the player is less aware of his real environment and focuses on the virtual environment.

- **Total Immersion**

The game atmosphere needs to be enhanced in order to achieve a complete immersion in the virtual environment. It consists of graphics, storyline and sound. The features of the game have to correspond with the game action and location. The virtual environment should influence the so-called *Flow*. It is a state of focus so oriented that it allows for complete absorption of the action [5].

The effect of immersion can appear on various types of devices. Yildirim et al. [6] have studied how VR experience is different from traditional desktop games, in the context

of a first-person shooter video game. The computer display was compared with HDMs Oculus Rift and HTC Vive. A standard keyboard and mouse were used to control all platforms. In the study, the Game User Experience Satisfaction Scale [7] was used. Using HDM allows to experience more immersion than using PC displays. However, the results showed that VR technology, in this case, did not lead to greater satisfaction with the UX of the game compared to a desktop computer. This may be due to the steering system used. The computer keyboard and mouse are not a dedicated control tool in VE. They are adapted for desktop computers. Improper and uncomfortable control may have disturbed the sense of presence in the game. The authors point out that the results obtained may be related to users' habits of interacting with a desktop computer and better adjusting the game to the PC, due to a longer presence on the market.

Schmidt et al. [8] examined how a virtual environment affects the immersion of exergames. This is a combination of video game elements with physical activity. They compared a rowing ergometer without VE and a rowing ergometer in combination with CAVE environment and HDM HTC Vive. A rowing simulator was applied in the VE. They used the Player Experience of Need Satisfaction (PENS) questionnaire, Subjective Exercise Experiences Scale (SEES) and an interview with participants about their experience in a virtual environment. Players considered the following factors as the most important in the VR experience: the pleasure of use, immersion, a distraction from the exercises performed, challenge, feedback (visual effects), allowing to keep the rhythm in the game and practicality in relation to the use of virtual reality in training. The work shows that better results in the sense of presence and flow were present using VR systems than those without VR. The authors showed that using VE had a positive impact. Especially HDM system. The participants felt more motivated by the increased sense of presence. In 91 percent, participants chose HDM combined with a rowing simulator as the most motivating virtual environment.

Porter and Robb [9] have reviewed how users' opinions on HDM have changed since they became available on the consumer market two years ago. In the opinion of the players, good design is key to immersion. Good gameplay allows better immersion. Music and sound play an important role [10]. They are one of the elements of feedback from VE. They can cause more reaction than an image. The game consists of interactions, so it is important to be able to do things that the player expects, but also surprise him. Everything that is within the player's reach should have an interaction. The game becomes more interesting and the immersion increases. It was attractive for players to be able to operate with their own hands. This made the immersion more realistic. The players were not influenced by the type of image, it did not have to be photorealistic. They paid more attention to the realization and functioning of the game. Improper rules of physics eliminated immersion. Sometimes the equipment itself became an obstacle to immersion. Players referred here to cables thrown out of the gameplay, missing frames, flickering, dead pixels. Such factors can also affect the unpleasant side effects of using VR technology.

2.3 Cybersickness

Cybersickness, also known as simulation disease, is a condition in which the person using the device feels discomfort when moving in a Virtual Environment [11]. It covers a number of symptoms of mobility sickness [12]. These include nausea, disorientation and the oculomotor. Nausea is associated with general discomfort and increased gastric

sensitivity. Disorientation includes dizziness and increased difficulty in concentration. Oculomotor symptoms include eyestrain, headache and fatigue [13]. This can be dangerous depending on the physical environment in which the user is located. The impact of virtual reality technology on users is a very individual issue. Some may be more vulnerable to cybersickness, others may not feel it at all. The issue of the impact of VR technology devices on users has been repeatedly researched. The most recent work in this field has been taken into account due to the very rapidly changing technology.

Yildirim [13] compared HDM devices (Oculus Rift CV1 and HTC Vive) with a traditional monitor. The first-person shooter game was used in combination with computer keyboard control and a racing game in which the Xbox controller was navigated. HDMs have dedicated controllers to control the virtual world, but they were not used for this purpose to compare devices with a monitor. Simulator Sickness Questionnaire (SSQ) [14, 15] was used to evaluate the results. In both cases a higher level of cybersickness was observed on HDM than on a traditional display. During a racing game, a higher overall level of cybersickness was obtained than in a shooter game. The authors find that this may be related to the required increased amount of head movement and the speed of movement. They also show that the deterioration in the perception of the virtual environment on HDM devices is related to the incompatibility of signals received by the vestibular system with the visual system. As the degree of mismatch increases, the cybersickness symptoms intensify. Palmisano et al. [16] and Kim et al. [17] focused on exploring this aspect. It has been shown that cybersickness and perception of scene instability increase with an artificially forced increase in display delays.

Guna et al. [18] examined, using SSQ [14, 15] and patient's physiological response, how two types of omnidirectional stereoscopic 3D videos affect the level of cybersickness. For the study, neutral video and action video were selected and displayed on TV display and HDM devices (three generations of Oculus Rift, Samsung GearVR). The results obtained show the lowest level of Sickness for the TV display. The results are comparable for both types of films. However, when using HDM, there is a significant difference depending on the type of film used. The differences in video reception on HDM devices were statistically insignificant. On the basis of the results, it was found that the users enjoyed more neutral material. This was also confirmed by the levels of physiological parameters, which did not differ from the initial level during neutral video. The study shows that video content in VE is an important factor for user experience.

In the study of the players' opinions on VR, there were also issues related to cybersickness [9]. One of the remarks made by consumers was the occurrence of a motion sickness when using the headsets. The causes of this condition were mainly the methods of movement used in games, such as teleportation, the user's moving field of view without headset movement, blocked reference points and insufficient (visual) feedback to show the player what is happening in the game.

2.4 Usability

The usability of the applied solution should be characterized by the variety and degree to which the system's functionalities can be used intuitively and effectively by the user. The main features include ease and efficiency in performing basic tasks, ease of reuse of resources and user satisfaction with using the system. To apply virtual reality technology as a physiotherapeutic or rehabilitation tool, the software must be adapted accordingly. This also applies to the system recipients. Postal and Rieder [19] have defined what

features an application for older people should have. The basic issue here is to maintain appropriate interaction. Serious games can help to stimulate activity and increase patient interest in treatment, which can often be slow and painful. The benefits of such games generally remain for weeks and can be transferred to daily activities.

Chapter 3

Application in Virtual Reality Technology

3.1 Assumptions

The main objective of the development of the application is to better adapt it to the needs of users and correct the observed deficiencies. The tests completed in the engineer's thesis [2] show that the application requires a stronger motivation system to encourage the user to continue playing. When the assignment became difficult for the patient, there was a desire to abandon the achieved progress and give up the gameplay. It is also required to diversify tasks and develop an interaction system to increase immersion. In the work, it was noted that the grasping system requires more precision. However, this is a feature of the Leap Motion device which is used. For this reason, it should be noted that the application is designed for patients who already have hand dexterity and is used to maintain and develop it. In the case of early rehabilitation, in a short period of time after the stroke, it may prove ineffective.

3.2 Software and Hardware

The same software as in the previous work was used to create the application: Unity 2018.1.6, Oculus SDK, Leap Motion SDK (Unity Core Assets 4.4.0, Leap Motion Interaction Engine 1.2.0, Hands Module 2.1.4, Graphic Renderer 0.1.3), Visual Studio 2017 was used to write scripts in C#, 3D models were created in Blender (some models are free objects downloaded from Unity Asset Store and Sketchfab).

The hardware used is HDM Oculus Rift and two sensors, Leap Motion, and notebook ASUS ROG Strix Scar II (Intel Core i7 processor, 16GB RAM, SSD, NVIDIA GeForce GTX 2070, Microsoft Windows 10 operating system) for easier testing of VR application.

3.3 Implementation

The application has been developed to minimize the possibility of unpleasant side effects. The gameplay provides a sitting position and eliminates any kind of movement in the VE, which is the most common cause of conflicting signals entering the vestibular system. The game requires only calm head movements. Attempts have also been made to preserve proprioception. This is ensured by the Leap Motion device and a graphic representation of the hand in the program. Users, thanks to hands control, can feel the

character in the VE and are aware of their body and movements transferred to the virtual system. The game is also adapted to the needs of users unfamiliar with VR equipment. The application does not require any settings, and the game can be started after the headset is applied.

3.3.1 Application Appearance

The 3D models selected for the game use low poly graphics. This means that their polygon mesh consists of fewer polygons. This allows for easier and quicker model making, and increases application optimization. This reduces the load on hardware. The resulting appearance contributes to a safe environment. Photorealistic elements can influence cybersickness. The graphic style of the game itself is not as important for immersion as interactions and feedback.

3.3.2 Interaction system

Interactive elements have been added to the game. This allows for increased user feedback from the virtual environment. The game has a friendly and calm background music that goes through all levels. At the relevant moments, a narration appears, explaining the task to be performed. This is an additional explanatory element in addition to the instructions on the boards. Moreover, sound effects were added to the performed tasks. If the user performs the exercise correctly, a sound is played to inform about it. Additionally, animations depending on the task were added. Graphical objects are also displayed to show how to perform the task correctly. This is an attempt to involve the user in the gameplay.

3.3.3 Gameplay

The game starts by greeting the user and presenting the way his/her hands work in the virtual system so that he/she can perform subsequent tasks aware of the current control (Figure 3.1). After the narration presented, the scene changes automatically. The tasks are ranked according to their difficulty level. There are 60 seconds for each. After this time, the scene is switched. Tasks instructions are shown in the narrative and the visible boards.



Figure 3.1: View of scene one

The first exercise involves grabbing balls suspended in space. When the ball is touched, they brighten up and interactive objects appear. In the middle of the screen, a white circle appears as in Figure 3.2. This is the indicator of the time for which the ball should be grabbed. It should be held as long as the disappearing circle is visible and when it appears to grab the balls again. After the appropriate gripping, a 3D object animation is played in front of the user. The remaining assignments are designed to be performed with one hand or according to the patient's needs. People after a stroke usually experience paresis in one hand, depending on which hemisphere is affected by the stroke. The next task is to move the emerging balls, indicated by interactive arrows, into a container (Figure 3.3). With each correct action, a voice signal is revealed, the number of balls present in the container is calculated and animated 3D objects appear. In the third task, the ball should be placed on the green field which appears (Figure 3.4). After correctly performed actions, a success sound and animation with 3D objects will occur. The last task (Figure 3.5) is based on the same principle as the second assignment. In this case, the balls must be placed in a suitable container. Also here the interactions appear after a properly performed exercise. In order to increase the usability of the created system, a tool for tracking the movements performed in the application was implemented. This allows to assess the correctness and check the progress of rehabilitation.



(a)



(b)



(c)

Figure 3.2: (a) Initial scene view of the first task in the application (b) Final scene view of the first task in the application (c) Scene with first task during the game.



(a)



(b)



(c)

Figure 3.3: (a) Initial scene view of the second task in the application (b) Final scene view of the second task during the game (c) Scene with second task during the game.



(a)



(b)

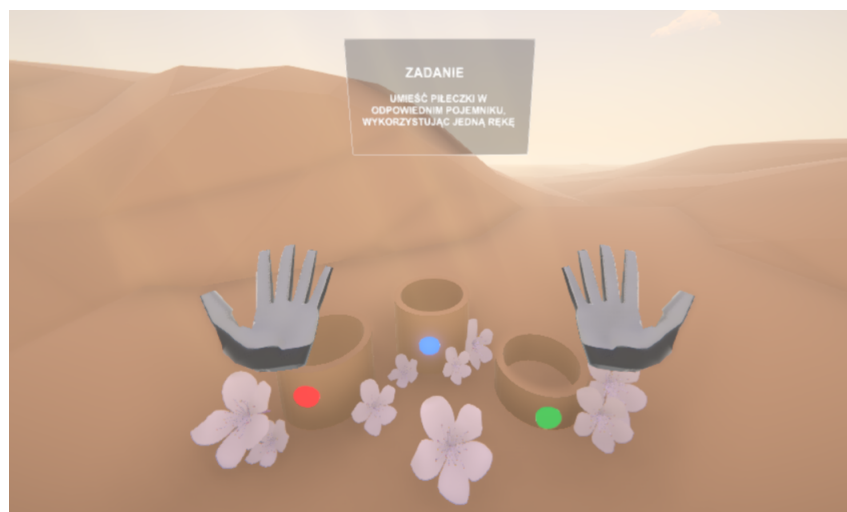


(c)

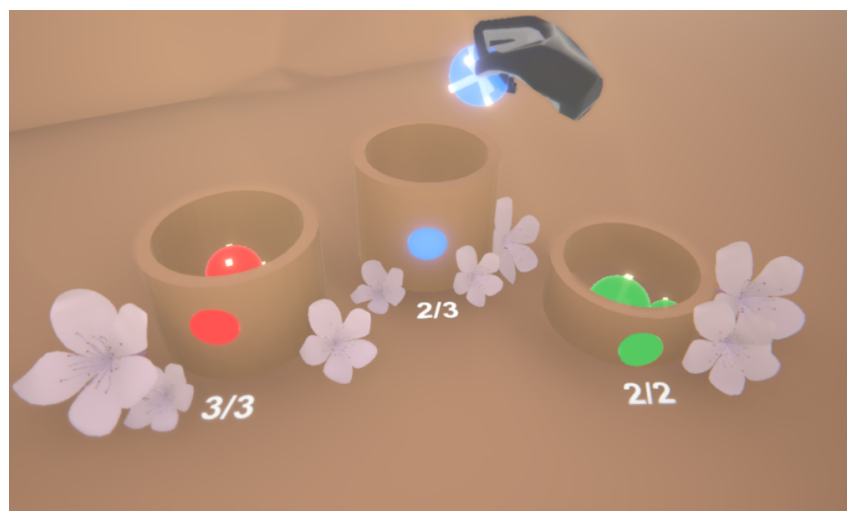
Figure 3.4: (a) Initial scene view of the third task in the application (b) Final scene view of the third task in the application (c) Scene with third task during the game.



(a)



(b)



(c)

Figure 3.5: (a) Initial scene view of the fourth task in the application (b) Final scene view of the fourth task in the application (c) Scene with fourth task during the game.

Chapter 4

Methods of assessing the effectiveness of the rehabilitation

In order to increase the usability of the created system, a tool for tracking the movements performed in the application was implemented. This allows to assess the correctness and check the progress of rehabilitation.

4.1 Review of methods for assessing rehabilitation effectiveness

Existing measures have been examined in order to create a suitable method to verify the progress of rehabilitation. The focus was on the methods collected by The Shirley Ryan AbilityLab [20]. The database of methods presented by the research centre is significant and overlaps with those used in most centres. Searches for existing methods included those used in the upper limbs poststroke rehabilitation.

Eighteen methods designed to verify the condition of patients after a stroke were studied. The methods are presented in the Table 3.1. Their area of assessment and type of assessment is specified. In the case of the type of assessment, three groups were divided. These include performance measure, observer, patient-reported outcomes. Performance measure refers to methods using evaluation of correctness and efficiency of performed tasks, which are administered by the clinician. The clinician assesses the performed exercise using a scale designed for this purpose, according to the method. The type of method observer is based on the assessment of the patient's skills by means of various types of observations. In NHTP [21] the result is the amount of time needed to perform the test and remove all 9 pins. In the Motricity Index [22], on the other hand, muscle strength is tested using a weighted score based on a 6-point linear scale. Tasks used for these methods are mainly exercises that examine the range of functional mobility such as lifting, grasping and total movement of the limbs. The methods using the patient-reported outcomes consist of filling in a questionnaire in which the patient estimates the degree of everyday activities and the impact of stroke on quality of life. The answer is given in points. In the case of SIS [23], it is a scale from 1 to 5. Based on the obtained result, the patient's mobility is evaluated. All the presented methods are an additional element of rehabilitation and often their results can be influenced by subjective evaluation of the observer or patient. The patient's feelings may differ from the reality, therefore the results obtained may be misleading.

Table 4.1: Methods for assessing rehabilitation effectiveness.

Method	Area of Assessment	Assessment Type
Performance Assessment Self-Care Skills (PASS) [24]	activities of daily living balance – vestibular cognition coordination dexterity executive functioning functional mobility hearing occupational performance reading comprehension reasoning/problem solving seating strength upper extremity function vision and perception	PERFORMANCE MEASURE
Motor Evaluation Scale for Upper Extremity in Stroke (MESUPES) [25]	dexterity range of motion upper extremity function	PERFORMANCE MEASURE
ABILHAND [26]	activities of daily living dexterity upper extremity function	PATIENT REPORTED OUTCOMES
Motricity Index [22]	upper extremity function functional mobility	OBSERVER
Rivermead Motor Assessment (RMA) [27]	functional mobility	PERFORMANCE MEASURE
Duruoz Hand Index (DHI) [28]	activities of daily living coordination dexterity functional mobility general health life participation upper extremity function	PERFORMANCE MEASURE
Nine-Hole Peg Test (NHTP) [21]	dexterity upper extremity function	OBSERVER
Wolf Motor Function Test (WMFT) [29]	dexterity strength upper extremity function	PERFORMANCE MEASURE
Action Research Arm Test (ARAT) [30]	activities of daily living coordination dexterity upper extremity function	OBSERVER

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Table 4.1 – *Continued from previous page*

Method	Area of Assessment	Assessment Type
Stroke Impact Scale (SIS) [23]	activities of daily living cognition communication depression functional mobility gait general health life participation quality of life social relationships social support upper extremity function	PATIENT REPORTED OUTCOMES
Stroke Rehabilitation Assessment of Movement (STREAM) [31]	coordination functional mobility range of motion	PERFORMANCE MEASURE
Jebsen Hand Function Test (JTHFT) [32]	activities of daily living upper extremity function	PERFORMANCE MEASURE
Sollerman Hand Function Test (SHFT) [33]	functional mobility	PERFORMANCE MEASURE
Hand Held Myometry/ Dynamometry [34]	strength	PERFORMANCE MEASURE
Quality of Life in Neurological Disorders (Neuro-QOL) [35]	activities of daily living attention and working memory behavior cognition communication depression executive functioning functional mobility life participation mental health negative affect occupational performance pain patient satisfaction positive affect quality of life social relationships social support sleep stress and coping	PATIENT REPORTED OUTCOMES

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Table 4.1 – *Continued from previous page*

Method	Area of Assessment	Assessment Type
Continuous Scale Physical Functional Performance (CS-PFP) [36]	activities of daily living balance – non-vestibular coordination functional mobility gait general health strength upper extremity function	PERFORMANCE MEASURE
Arm Motor Ability Test (AMAT) [37]	activities of daily living upper extremity function	PERFORMANCE MEASURE
Chedoke Arm and Hand Activity Inventory (CAHAI) [38]	activities of daily living upper extremity function	PERFORMANCE MEASURE

4.2 Method using hand tracking

A tool has been developed to examine progress in rehabilitation. All characteristics and disadvantages of existing and commonly used methods have been taken under consideration. There was a focus on eliminating the role of the assessment person that could influence the results. However, the participation of a physician or physiotherapist was not excluded. Another issue was to include the evaluation of the patient's results in daily exercises to check progress and verify mistakes on an ongoing basis. The described methods included different assessment areas. The assessment system was attempted to standardize, so that depending on the exercises used, the evaluation method was the same. This allows to investigate different functionalities by selecting sets of activities according to the patient's needs.

The project is based on hand tracking, which is provided by Leap Motion *Application Programming Interface* (API). An application has been created to record coordinates of position in time. Such a solution was previously proposed by the author [39]. Ona et al. [40] also presented a similar approach in the rehabilitation of Parkinson's patients. Research has shown that such a system has the potential to be applied in clinical conditions. The application was created with the help of Michał Olech, BEng. The Qt framework and C++ language were used to create this software.

4.2.1 Recording of movements

During the use of the system for virtual rehabilitation, the prepared software should be activated. The appearance of the application is presented on Figure 4.1. In the application window, choose the *Turn On Camera* button. If the device is correctly connected, the information "*Camera is connected*" is displayed. Before recording, it is possible to enter the name or number of the patient and select the approach number at the bottom of the window. This will allow to keep the file system in order, which names will be accompanied by the entered information with the recording date. A separate session is created for each rehabilitation task. The session time should also be selected. After this time the

recording will be completed. The files will be saved in the *Output* folder in CSV format. An additional option is to prepare time setting patterns for different exercises and select them from the lower part of the window by choosing the appropriate number. To record hand position while using Leap Motion, select *Start Recordings* button. The coordinates of the hand positions are displayed in the application during recording.

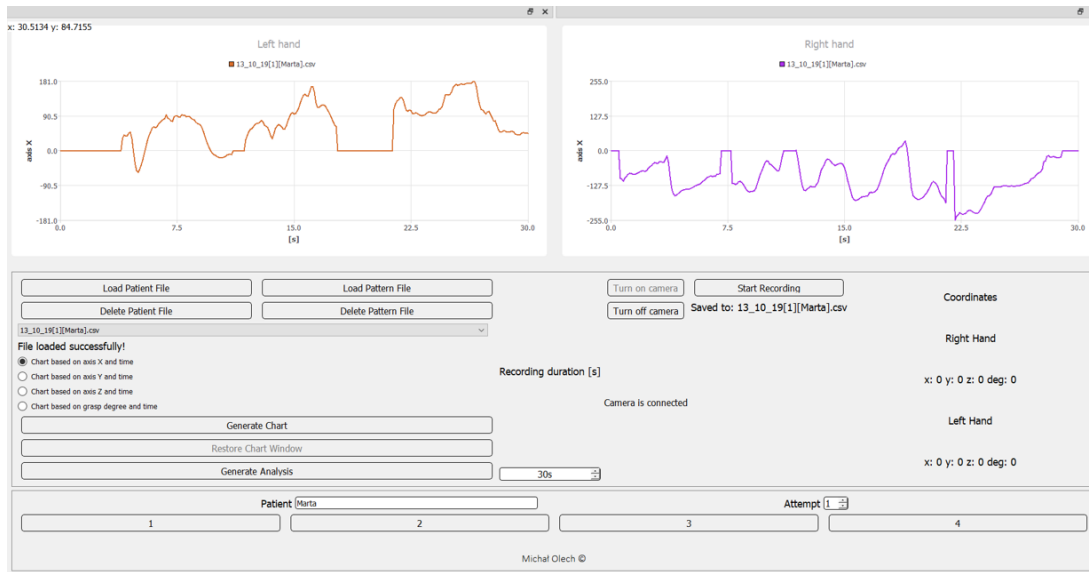


Figure 4.1: Application window layout.

4.2.2 Loading charts

The application allows to display all desired charts by loading them from a file, where they were previously saved. For this purpose, select the Load Patient File button, then choose for which axes the chart should be displayed and select Generate Chart. The graphs show the movement for each axis of the coordinates and the opening angle of the hand. The angle is measured between the plane of the hand and the plane formed by four fingers, without the thumb. Zero degrees means that the hand is clenched. It is also possible to exclude individual graphs from the application window by clicking Delete Patient File. In addition, selecting Generate Analysis will calculate the length of the saved path and the time the hand was open. This data will be written to the CSV file in the Analysis folder.

4.2.3 Comparison of data

There is a possibility to compare multiple tracks in one chart using the *Load Pattern File* option. Like before, select from the file the patient session and the path to be included and the *Generate Chart* button. The main purpose of the application is to verify how the patient's movements relate to the correct movements of a healthy person. This can be done by adding a template path to the registered patient path. This allows you to capture detailed differences and errors in patient movement for each coordinate axis. Also due to the length of the path and the time for which the hand has been open it is possible to obtain feedback on the user's movement. This makes possible to compare the patient's subsequent approaches to the exercises and observe on the obtained curves if his/her movements have changed and to react to any mistakes.

The developed tool can also be used for other hand movement measurement applications. This is a separate software application that requires a Leap Motion device and a computer. Thus, after placing hands in the device's field of vision, the application can be used for conventional physiotherapy.

Chapter 5

Tests

The developed system for poststroke rehabilitation was tested. For this purpose, a testing stand for the game was prepared, consisting of a computer and two Rift sensors placed on the desk, HDM Oculus Rift, Leap Motion device and a chair. Previously, the equipment was calibrated for proper head and hand detection, as well as for providing a safe playing area. Testers used the system in a sitting position. The game time did not exceed 5 minutes.

The tests were attended by 5 participants aged 18-73, including 2 women and 3 men. 2 testers had previously used VR technology, for the others it was their first contact with this type of equipment. Everyone had normal physical fitness. They were not under the influence of alcohol or medication. Their approach to testing was different. Testers 1 and 3 feel the effects of a motor sickness in their daily lives.

In the study used:

- **Simulator Sickness Questionnaire (SSQ)** [15, 14]

SSQ is a tool used to assess the degree of cybersickness. The questionnaire includes 26 symptoms and based on a subjective evaluation of its severity on a 4-point scale, from the absence of symptoms (0) to its significant impact on the user (3). The result of SSQ is the total level of cybersickness (TS) and its constituent subscales: nausea (N), oculomotor (O), disorientation (D). The questionnaire was filled in by testers before and after using the rehabilitation system.

- **Game User Experience Satisfaction Scale (GUESS)** [7]

Additionally, it has been verified how the game affects user satisfaction. The GUESS tool was used for this purpose. In this method, the player's experience is measured using 9 factors such as: Usability/Playability, Narratives, Play Engrossment, Enjoyment, Creative Freedom, Audio Aesthetics, Personal Gratification, Social Connectivity, Visual Aesthetics. The study excluded 3 factors Narratives, Creative Freedom and Social Connectivity and some of the questions marked N/A, because of the lack of reference in the developed application. Each of the factors contains questions about a given aspect. They are evaluated on a 7-point scale (Strongly Disagree (1), Disagree (2), Somewhat Disagree (3), Neither Agree or Disagree (4), Somewhat Agree (5), Agree (6), Strongly Agree (7)). Testers answered the questions after using the VR system.

Chapter 6

The result

The tests verified the functionality of the created system, which includes the VR application for exercises and a tool for recording the position of hands. The results obtained are presented below.

6.1 Hand tracking

The position of the users' hands in each task was recorded. The obtained paths were saved as charts. The paths accomplished by the testers in the first task for all three axes and for the degree of hand opening are presented in an overview (Figure 6.4). The movement in the task is repetitive and quite easy to verify its correctness. The motions performed by users overlap. In Figures 6.1 and 6.2 for the right hand of Tester 5, large-amplitude movements are visible, differing from the whole path. This is due to incorrect detection of the hand by the Leap Motion device. Sometimes such a situation occurred during the game when, for example, two hands were too close to each other or were outside the device's field of view. Figure 6.4 shows the degree of hand opening for Tester 2. A template path is included to show how the movements can be compared to the measured path. It was attempted to prepare it in a way that it indicates when the palms are sufficiently open. This means that if the patient's movement path is above the template path, hands are properly opened. As is the case here.



Figure 6.1: Registered tester paths for task one, axis x.

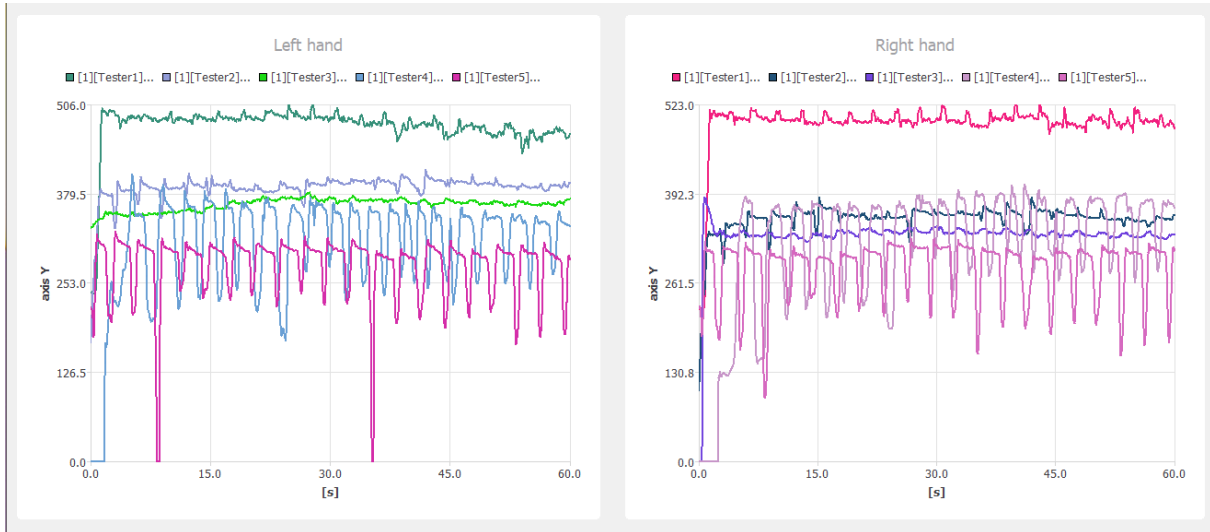


Figure 6.2: Registered tester paths for task one, axis y.

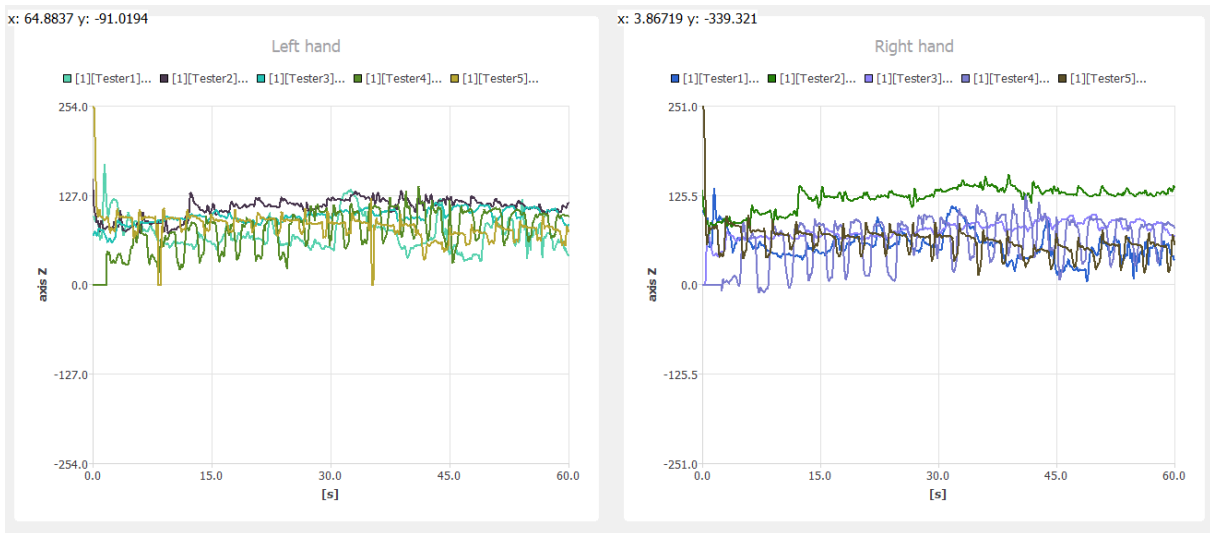


Figure 6.3: Registered tester paths for task one, axis z.

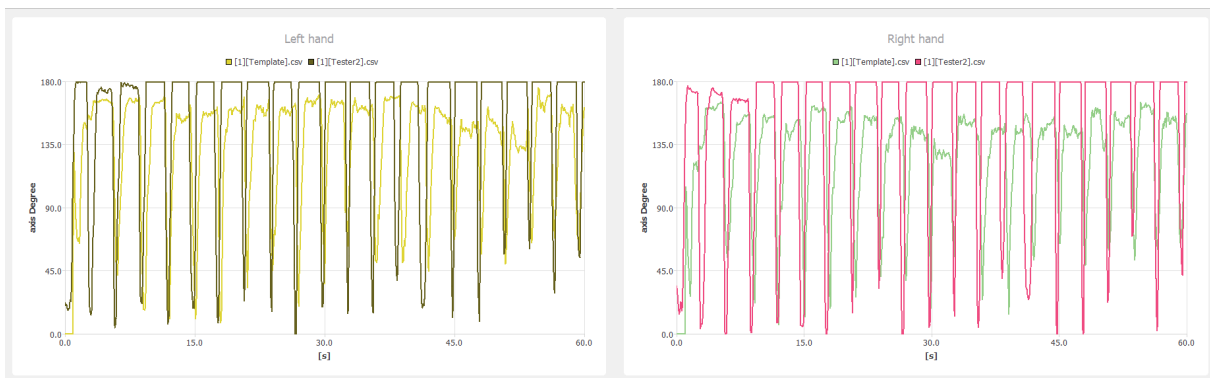


Figure 6.4: Comparison of the movements of Tester 2 with the reference path for task one, hand opening degrees.

In the registration of some exercises, it is impossible to accurately compare the obtained paths due to too much possibility of hand movement during exercises. This is

shown in Figures 6.5 - 6.7 for the fourth task. In this case, it would be better to prepare a range of coordinates in time for the correct paths, or to make the moves more determined and limit them in the game. Table 6.1 shows the lengths of the paths achieved by the testers, which can be used to evaluate the accuracy of their moves.

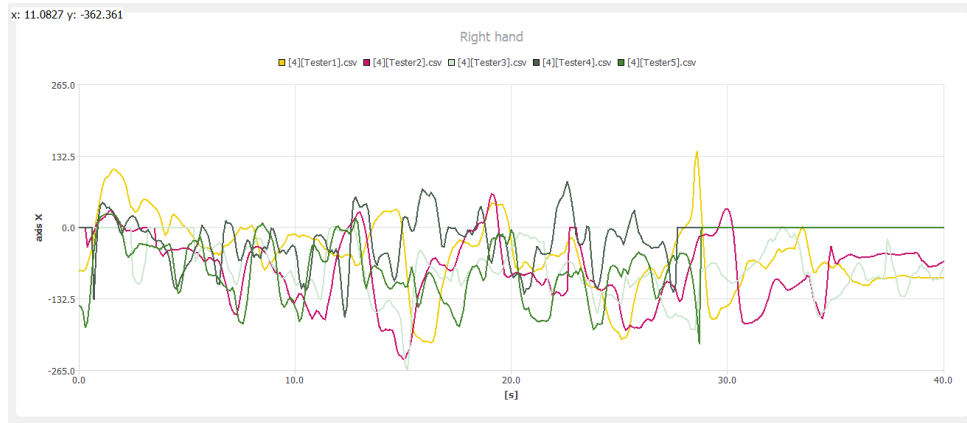


Figure 6.5: Registered tester paths for task four, axis x.



Figure 6.6: Registered tester paths for task four, axis y.

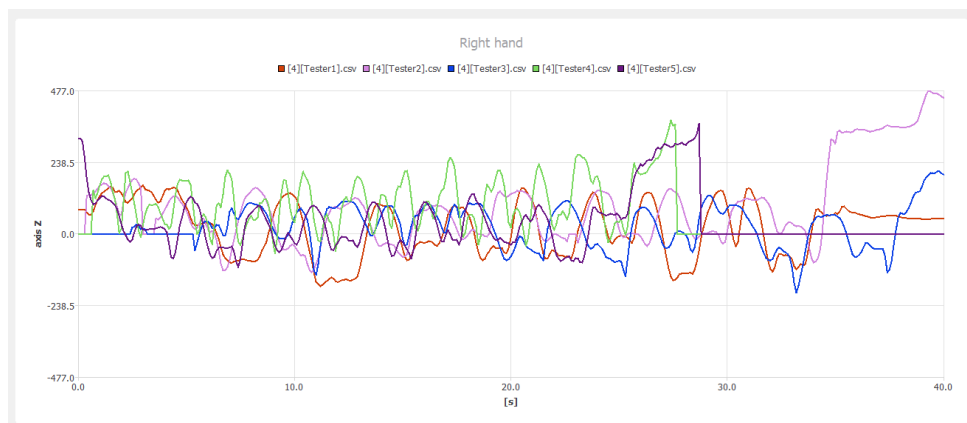


Figure 6.7: Registered tester paths for task four, axis z.

Several problems were encountered while using the application. Registration of movements during the exercises may have affected the immersion of users, because for each task

Table 6.1: Track lengths for axes (x, y, z) and hand opening time in seconds (s).

Task1								
Left Hand					Right Hand			
	x	y	z	s	x	y	z	s
Tester1	1804,31	1862,70	2118,50	43,99	1823,04	2023,70	1958,38	43,93
Tester2	2827,25	3560,64	3570,46	44,00	2821,42	3813,57	3300,17	43,91
Tester3	3679,90	4398,32	4544,30	44,07	3838,11	5139,00	4292,84	43,98
Tester4	6699,08	10761,30	7795,65	44,20	5812,49	11544,90	7998,01	50,10
Tester5	10047,20	16167,20	10227,70	57,10	7278,41	17016,60	10614,50	64,10

it was necessary to re-enter the data in the application and enable recording. This caused a small delay for the player and an additional person was needed for this. This could have been avoided by automatically activating the application during game task changes or by fully integrating it with the VR application. None of the testers complained about these issues, but it could improve the gameplay and make the player self-sufficient when using the verification system.

6.2 Simulator Sickness Questionnaire (SSQ)

Simulator Sickness Questionnaire was used to assess the impact of the application on the user's condition. The charts show the results achieved (Figure 6.8, 6.9). Statistical analysis was omitted due to the small test group. The attitude of users before and after tests of the rehabilitation system was compared. As can be seen in the charts, the application influenced testers in different ways.

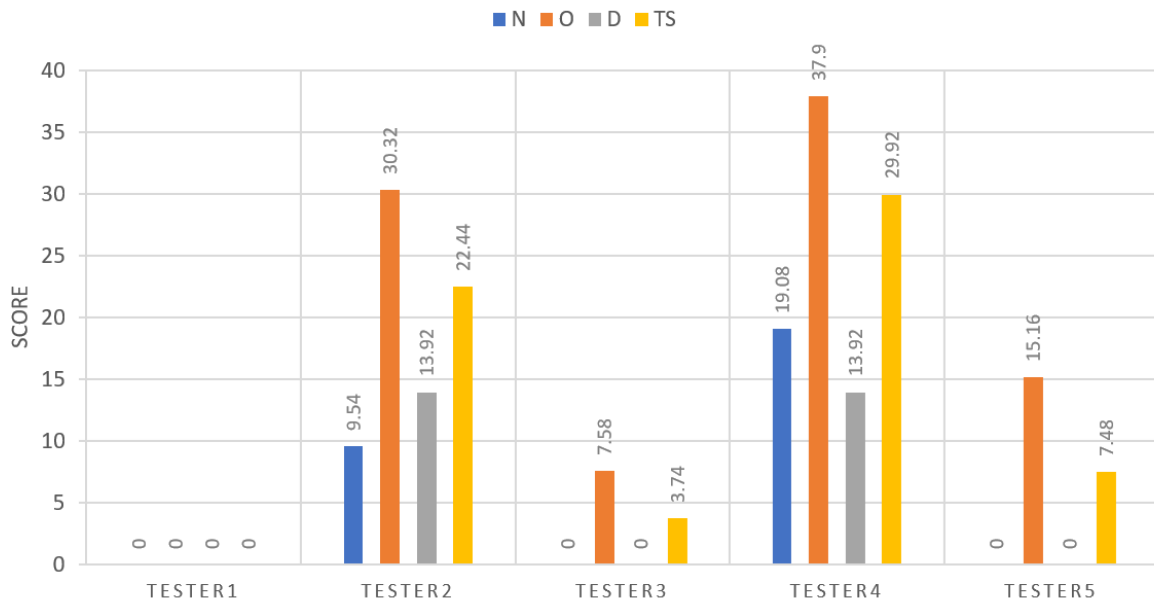


Figure 6.8: SSQ results before the rehabilitation system.

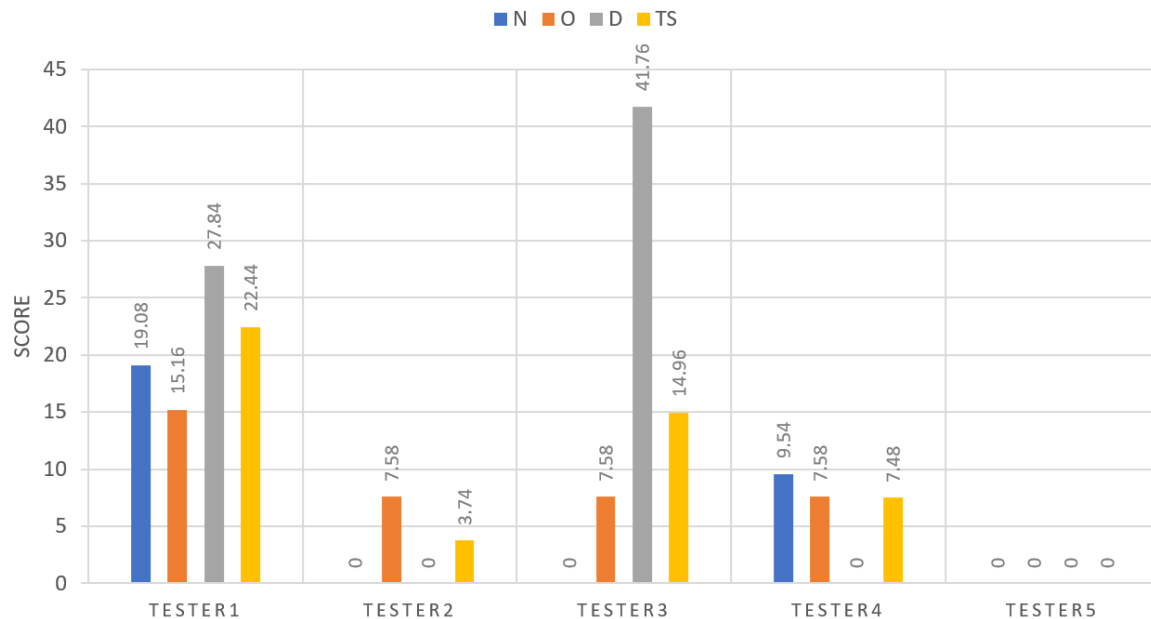


Figure 6.9: SSQ results after using the rehabilitation system.

After using the application, the general condition of Tester 1 deteriorated, and the intensity of the symptoms that constitute it increased. The highest result reached disorientation. This may be due to a temporary image leap during the game. This was a one-time situation that was not repeated with other testers and could be related to too much equipment load. The tester has a motion sickness so it could have affected his or her feelings even more severely. Tester 3 also suffers from a motion sickness, and here also the worsening of condition is visible. Especially in case of disorientation. The surprising fact is that after using the application the intensity of some ailments present before the test has decreased. Tester 2 felt improved. He/she also noticed that thanks to the application he improved his concentration and felt less sleepy. The same situation occurred with tester 4 and 5.

Thus, the application affected users during testing in two ways. It is also important to note the maximum possible value of the calculated indicators, which are as follows N:200,34; O:159,18; D:292,32; TS:235.62. This shows that the results achieved in the tests are relatively small and the application does not pose a health risk. However, it can affect their well-being, although this issue is very individual.

6.3 Game User Experience Satisfaction Scale (GUESS)

After the tests, users answered the questions included in the Game User Experience Satisfaction Scale. The answers of all testers have been converted into numerical values and are presented as an average in Tables 6.2-6.7. Also, in this case, the statistical analysis was omitted due to the size of the test group.

The results achieved are satisfactory. It proves good reception of the application by users. The answers to the questions are often close to the maximum result. However, in some cases, some improvements could be made. This applies for example to Factor 3 (Play Engrossment). Making the game more varied and prolonged would improve the user's involvement, which could contribute to the desire to play for longer and to lose the sense of time. During testing, time was limited. Factor 7 (Personal Gratification) is another

worth improving. Here, a way of rewarding the user could be developed, which would increase the pleasure of achieving further goals in the game. Improving skills in the game was relatively difficult due to one-off gameplay. However, with each task testers got used to the system and the performance of the tasks went better. Following this lead, simplifying and adapting the task instructions accordingly would make it easier to understand the goals to achieve at a given level. This could improve Factor 1 (Usability/Playability) performance.

Table 6.2: GUESS Factor 1 (Usability/Playability)

Factor 1 (Usability/Playability)	
<i>Item</i>	<i>M</i>
I think it is easy to learn how to play the game.	6,0
I find the controls of the game to be straightforward.	6,0
I always know how to achieve my goals/objectives in the game.	6,2
I find the game's interface to be easy to navigate.	6,6
I do not need to go through a lengthy tutorial or read a manual to play the game.	6,2
I find the game's menus to be user friendly.	N/A
I feel the game trains me well in all of the controls.	6,2
I always know my next goal when I finish an event in the game.	6,4
I feel the game provides me the necessary information to accomplish a goal within the game.	6,2
I think the information provided in the game (e.g., onscreen messages, help) is clear.	6,4
I feel very confident while playing the game.	6,2

Table 6.3: GUESS Factor 3 (Play Engrossment)

Factor 3 (Play Engrossment)	
<i>Item</i>	<i>M</i>
I feel detached from the outside world while playing the game.	6,4
I do not care to check events that are happening in the real world during the game.	6,6
I cannot tell that I am getting tired while playing the game.	6,8
Sometimes I lose track of time while playing the game.	3,6
I temporarily forget about my everyday worries while playing the game.	6,4
I tend to spend more time playing the game than I have planned.	N/A
Whenever I stopped playing the game I cannot wait to start playing it again.	5,8

Table 6.4: GUESS Factor 4 (Enjoyment)

Factor 4 (Enjoyment)	
<i>Item</i>	<i>M</i>
I think the game is fun.	6,4
I enjoy playing the game.	6,4
I feel bored while playing the game.	2,4
I am likely to recommend this game to others.	6,4
If given the chance, I want to play this game again.	6,2

Table 6.5: GUESS Factor 6 (Audio Aesthetics)

Factor 6 (Audio Aesthetics)	
<i>Item</i>	<i>M</i>
I enjoy the sound effects in the game.	6,0
I enjoy the music in the game.	6,2
I feel the game's audio (e.g., sound effects, music) enhances my gaming experience.	7,0
I think the game's audio fits the mood or style of the game.	6,4

Table 6.6: GUESS Factor 7 (Personal Gratification)

Factor 7 (Personal Gratification)	
<i>Item</i>	<i>M</i>
I am in suspense about whether I will succeed in the game.	4,6
I feel successful when I overcome the obstacles in the game.	6,0
I want to do as well as possible during the game.	6,6
I am very focused on my own performance while playing the game.	6,4
I feel the game constantly motivates me to proceed further to the next stage or level.	6,6
I find my skills gradually improve through the course of overcoming the challenges in the game.	4,6

Table 6.7: GUESS Factor 9 (Visual Aesthetics)

Factor 9 (Visual Aesthetics)	
<i>Item</i>	<i>M</i>
I enjoy the game's graphics.	6,6
I think the graphics of the game fit the mood or style of the game.	6,4
I think the game is visually appealing.	6,6

Chapter 7

Opportunities for system development

Testing the application allowed to determine which parts of the system should be improved or developed. Improvement is required in the application registering hand movements, which is used to assess progress in rehabilitation. Daily use by a sick person may become problematic. Its advantage is that it can work with various applications integrated with Leap Motion. It would be used for periodic examination with an additional person, but may not be sufficient for home therapy. In this case, the evaluation system built into the application would perform better, working automatically in real-time. In this way, it would be possible to inform the user directly during the game about the mistakes made. The use of the Leap Motion device itself should also be considered. As confirmed by the tests, it does not always detect the position of the hand well and therefore can make everyday exercises difficult. Many new devices are currently being developed, such as HDM Oculus Quest, which does not need any additional equipment to read the hand movement, because the sensors have been placed in the headset. An additional advantage is that it is autonomous. This means that it does not need to be connected to a computer with cables. This gives the user more freedom and increases immersion. However, the hand tracking software has been released in beta version, it would have to be tested for usability of patients after a stroke before they are introduced into the rehabilitation system.

Another aspect is the development of VR applications. As research has shown, it requires more tasks and a better reward system. The solution could be to introduce the story to the game. Then the user will perform tasks following the flow of entertainment. The game would become more engaging and involving for the user. The tasks could be adjusted to the created story. The user would perform a different exercise each time, on similar principles as in the current system, or repeat it in case of failure. This would avoid being bored with the game. The storyline would motivate the user to overcome further obstacles. Also, the current instructions in the game need to be improved. In addition to the narrative used, hand animations could be introduced to show how to perform the tasks. This would be available for the user's first approach to the task, as it could be boring after a while. Another improvement can be the introduction of online gameplay with other players. Social interactions can increase the player's involvement in the game and intensify the immersion [9].

The created rehabilitation system is a good basis for further development. After continuing improvements to the system, it will be necessary to check it on stroke patients and consult the physician. For this purpose, a request for testing will be required from the Bioethics Committee.

Chapter 8

Conclusion

The aim of the study was to build a computer-aided rehabilitation system for stroke patients. Two applications were created as part of the system: an application for VR exercises and a hand tracking application to assess the progress of the exercises.

In order to develop a proper medium for rehabilitation, research was conducted. It was verified how a safe and useful application in virtual reality technology should be, to ensure that it does not endanger patients' health, is pleasant to use and brings benefits in terms of improving physical fitness. A literature review focusing on VR technology and the collected opinions of users was conducted. On the basis of the collected information, the VR application for exercises developed previously in the engineer's thesis [2] was expanded. Afterwards, tests have been conducted to find out how the improvement of the application performs in practical usage.

The same procedure was applied to the application to assess progress in the rehabilitation process. The existing and currently used methods of evaluation of poststroke revalidation were analysed. The idea behind the creation of the application was to exercise daily and check how the user handles the undertaken tasks. It was also intended to reduce the number of accessories needed for such an assessment, to avoid the subjective impression of the assessor and to create a universal tool that would allow for everyday use. In this way, a system was created using the equipment already used for VR applications. It only uses the Leap Motion device, so it can be used for other applications integrated with this tool. The basis for the evaluation is a comparison of recorded by Leap Motion hands positions. The tool was also examined with the VR application tests.

The measurements were conducted on 5 testers. The impact of the VR application on the user was analysed. It was verified whether it causes cybersickness. It was also evaluated how it works with the instrument for hands position recording. Thanks to the results obtained in the tests, it was determined in which direction to conduct development actions on the created system. The length of the game should be extended. A useful and motivating aspect would be to introduce the plot while performing the exercises. The application for hands tracking and assessment of rehabilitation progress should be embedded in the VR application. This would make the whole system easier to use. The conclusion is also drawn that the equipment used in the system should be reconsidered. Virtual reality technology is developing very rapidly and it is possible that a better hardware proposal for use in rehabilitation will soon be available. The possible solutions should be explored and the most appropriate, i.e. simple, convenient and patient-friendly solution should be selected.

The system achieved in the work is a good basis for further development. It is possible to further advance the application already with the project team. Perhaps it will

allow in the future for the practical application of this type of system in home poststroke rehabilitation. It would be a great facilitation and variety in conventional therapy. The application, in addition to allowing the development of physical abilities, is also an entertainment and detachment from the daily difficulties faced by patients. Thus, it can have a positive impact on both physical and mental health of the patients and, consequently, a faster recovery.

Bibliography

- [1] K. E. Laver, B. Lange, S. George, J. E. Deutsch, G. Saposnik, and M. Crotty, "Virtual reality for stroke rehabilitation," *Stroke*, vol. 49, no. 4, pp. e160–e161, 2018.
- [2] M. Marzec, "Zastosowanie technologii wirtualnej rzeczywistości (VR) w rehabilitacji poudarowej." Thesis (B.Eng.), 2018.
- [3] M. Slater, V. Linakis, M. Usoh, and R. Kooper, "Immersion, presence and performance in virtual environments: An experiment with tri-dimensional chess," in *Proceedings of the ACM symposium on virtual reality software and technology*, pp. 163–172, 1996.
- [4] E. Brown and P. Cairns, "A grounded investigation of game immersion," in *CHI'04 extended abstracts on Human factors in computing systems*, pp. 1297–1300, 2004.
- [5] M. Csikzentmihalyi, "Flow, the psychology of optimal experience. 1990."
- [6] C. Yildirim, M. Carroll, D. Hufnal, T. Johnson, and S. Pericles, "Video game user experience: To vr, or not to vr?," in *2018 IEEE Games, Entertainment, Media Conference (GEM)*, pp. 1–9, IEEE, 2018.
- [7] M. H. Phan, J. R. Keebler, and B. S. Chaparro, "The development and validation of the game user experience satisfaction scale (guess)," *Human factors*, vol. 58, no. 8, pp. 1217–1247, 2016.
- [8] S. Schmidt, P. Ehrenbrink, B. Weiss, J.-N. Voigt-Antons, T. Kojic, A. Johnston, and S. Möller, "Impact of virtual environments on motivation and engagement during exergames," in *2018 Tenth international conference on quality of multimedia experience (qoMEX)*, pp. 1–6, IEEE, 2018.
- [9] J. Porter III and A. Robb, "An analysis of longitudinal trends in consumer thoughts on presence and simulator sickness in vr games," in *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, pp. 277–285, 2019.
- [10] M. Covarrubias, B. Aruanno, T. Cianferoni, M. Rossini, S. Komarova, and F. Molteni, "Neuro rehabilitation system through virtual reality, music and fragrance therapy," in *International Conference on NeuroRehabilitation*, pp. 848–852, Springer, 2018.
- [11] U. A. Chattha and M. A. Shah, "Survey on causes of motion sickness in virtual reality," in *2018 24th International Conference on Automation and Computing (ICAC)*, pp. 1–5, IEEE, 2018.
- [12] R. S. Kennedy, J. Drexler, and R. C. Kennedy, "Research in visually induced motion sickness," *Applied ergonomics*, vol. 41, no. 4, pp. 494–503, 2010.

- [13] C. Yildirim, “Don’t make me sick: investigating the incidence of cybersickness in commercial virtual reality headsets,” *Virtual Reality*, pp. 1–9, 2019.
- [14] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, “Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness,” *The international journal of aviation psychology*, vol. 3, no. 3, pp. 203–220, 1993.
- [15] M. P. Biernacki, R. S. Kennedy, and Ł. Dziuda, “Zjawisko choroby symulatorowej oraz jej pomiar na przykładzie kwestionariusza do badania choroby symulatorowej–ssq,” *Medycyna Pracy*, vol. 67, no. 4, pp. 545–555, 2016.
- [16] S. Palmisano, L. Szalla, and J. Kim, “Monocular viewing protects against cybersickness produced by head movements in the oculus rift,” in *25th ACM Symposium on Virtual Reality Software and Technology*, pp. 1–2, 2019.
- [17] J. Kim, M. Moroz, B. Arcioni, and S. Palmisano, “Effects of head-display lag on presence in the oculus rift,” in *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*, pp. 1–2, 2018.
- [18] J. Guna, G. Geršak, I. Humar, M. Krebl, M. Orel, H. Lu, and M. Pogačnik, “Virtual reality sickness and challenges behind different technology and content settings,” *Mobile Networks and Applications*, pp. 1–10, 2019.
- [19] M. R. B. Postal and R. Rieder, “Métodos de avaliação de interfaces de usuário para idosos: Uma revisão sistemática,” in *Anais do XXI Simpósio de Realidade Virtual e Aumentada*, pp. 103–110, SBC, 2019.
- [20] “Shirley Ryan AbilityLab.” <https://www.sralab.org/rehabilitation-measures>, 2020. [Online; accessed May 21, 2020].
- [21] V. Mathiowetz, K. Weber, N. Kashman, and G. Volland, “Adult norms for the nine hole peg test of finger dexterity,” *The Occupational Therapy Journal of Research*, vol. 5, no. 1, pp. 24–38, 1985.
- [22] G. Demeurisse, O. Demol, and E. Robaye, “Motor evaluation in vascular hemiplegia,” *European neurology*, vol. 19, no. 6, pp. 382–389, 1980.
- [23] P. W. Duncan, R. K. Bode, S. M. Lai, S. Perera, G. A. in Neuroprotection Americas Investigators, *et al.*, “Rasch analysis of a new stroke-specific outcome scale: the stroke impact scale,” *Archives of physical medicine and rehabilitation*, vol. 84, no. 7, pp. 950–963, 2003.
- [24] M. B. Holm, J. Rogers, and B. Hemphill-Pearson, “The performance assessment of self-care skills (pass),” *Assessments in occupational therapy mental health*, vol. 2, pp. 101–110, 2008.
- [25] A. Van de Winckel, H. Feys, S. Van Der Knaap, R. Messerli, F. Baronti, R. Lehmann, B. Van Hemelrijk, F. Pantè, C. Perfetti, and W. De Weerd, “Can quality of movement be measured? rasch analysis and inter-rater reliability of the motor evaluation scale for upper extremity in stroke patients (mesupes),” *Clinical rehabilitation*, vol. 20, no. 10, pp. 871–884, 2006.

- [26] M. Penta, J.-L. Thonnard, and L. Tesio, "Abilhand: a rasch-built measure of manual ability," *Archives of physical medicine and rehabilitation*, vol. 79, no. 9, pp. 1038–1042, 1998.
- [27] F. M. Collen, D. T. Wade, G. Robb, and C. Bradshaw, "The rivermead mobility index: a further development of the rivermead motor assessment," *International disability studies*, vol. 13, no. 2, pp. 50–54, 1991.
- [28] N. Sezer, G. Yavuzer, K. Sivrioglu, P. Basaran, and B. F. Koseoglu, "Clinimetric properties of the duruoz hand index in patients with stroke," *Archives of physical medicine and rehabilitation*, vol. 88, no. 3, pp. 309–314, 2007.
- [29] S. L. Wolf, P. A. Catlin, M. Ellis, A. L. Archer, B. Morgan, and A. Piacentino, "Assessing wolf motor function test as outcome measure for research in patients after stroke," *Stroke*, vol. 32, no. 7, pp. 1635–1639, 2001.
- [30] R. C. Lyle, "A performance test for assessment of upper limb function in physical rehabilitation treatment and research," *International journal of rehabilitation research*, vol. 4, no. 4, pp. 483–492, 1981.
- [31] K. Daley, N. Mayo, and S. Wood-Dauphinee, "Reliability of scores on the stroke rehabilitation assessment of movement (stream) measure," *Physical therapy*, vol. 79, no. 1, pp. 8–23, 1999.
- [32] R. H. Jebsen, N. Taylor, R. Trieschmann, M. J. Trotter, and L. A. Howard, "An objective and standardized test of hand function.," *Archives of physical medicine and rehabilitation*, vol. 50, no. 6, pp. 311–319, 1969.
- [33] C. Sollerman and A. Ejeskär, "Sollerman hand function test: a standardised method and its use in tetraplegic patients," *Scandinavian Journal of Plastic and Reconstructive Surgery and Hand Surgery*, vol. 29, no. 2, pp. 167–176, 1995.
- [34] R. Van der Ploeg, V. Fidler, and H. Oosterhuis, "Hand-held myometry: reference values.," *Journal of Neurology, Neurosurgery & Psychiatry*, vol. 54, no. 3, pp. 244–247, 1991.
- [35] D. Cella, J.-S. Lai, C. Nowinski, D. Victorson, A. Peterman, D. Miller, F. Bethoux, A. Heinemann, S. Rubin, J. E. Cavazos, *et al.*, "Neuro-qol: brief measures of health-related quality of life for clinical research in neurology," *Neurology*, vol. 78, no. 23, pp. 1860–1867, 2012.
- [36] M. E. Cress, D. M. Buchner, K. A. Questad, P. C. Esselman, B. J. DeLateur, and R. S. Schwartz, "Continuous-scale physical functional performance in healthy older adults: a validation study," *Archives of physical medicine and rehabilitation*, vol. 77, no. 12, pp. 1243–1250, 1996.
- [37] N. Yozbatiran, L. Der-Yeghiaian, and S. C. Cramer, "A standardized approach to performing the action research arm test," *Neurorehabilitation and neural repair*, vol. 22, no. 1, pp. 78–90, 2008.
- [38] S. Barreca, C. Gowland, P. Stratford, M. Huijbregts, J. Griffiths, W. Torresin, M. Dunkley, P. Miller, and L. Masters, "Development of the chedoke arm and hand activity inventory: theoretical constructs, item generation, and selection," *Topics in stroke rehabilitation*, vol. 11, no. 4, pp. 31–42, 2004.

- [39] M. Marzec, M. Olech, R. Klempous, J. Nikodem, K. Kluwak, C. Chiu, and A. Kołcz, “Virtual reality poststroke rehabilitation with localization algorithm enhancement,” in *The 5th International Conference of the Virtual and Augmented Reality in Education, VARE*, pp. 28–35, DIME Università di Genova : DIMEG University of Calabria, 2019.
- [40] E. D. Oña, A. Cuesta-Gomez, J. A. Garcia, W. Raffe, P. Sánchez-Herrera, R. Cano-de-la Cuerda, and A. Jardón, “Evaluating a vr-based box and blocks test for automatic assessment of manual dexterity: A preliminary study in parkinson’s disease,” in *2019 IEEE 7th International Conference on Serious Games and Applications for Health (SeGAH)*, pp. 1–6, IEEE, 2019.

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